

Westinghouse Non-Proprietary Class 3

WCAP-16530-NP-A

March 2008

Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191



WCAP-16530-NP-A

Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191

***Ann E. Lane**
Timothy S. Andreychek
Containment Systems Applications

William A. Byers
Richard J. Jacko
Materials and Corrosion Technologies

Edward J. Lahoda
Chemical Processing

Richard D. Reid
Chemistry, Diagnostics & Materials Engineering

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Approved: *William J. Rinkacs, Manager
Containment Systems Applications

***Gordon C. Bischoff, Manager**
Pressurized Water Reactor Owners Group

****Electronically approved records are authenticated in the Electronic
Document Management System.***

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Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

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SECTION A



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

December 21, 2007

Mr. Gordon Bischoff, Manager
Owners Group Program Management Office
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355

SUBJECT: FINAL SAFETY EVALUATION FOR PRESSURIZED WATER
REACTOR OWNERS GROUP (PWROG) TOPICAL REPORT (TR)
WCAP-16530-NP, "EVALUATION OF POST-ACCIDENT CHEMICAL EFFECTS
IN CONTAINMENT SUMP FLUIDS TO SUPPORT GSI-191" (TAC NO. MD1119)

Dear Mr. Bischoff:

By letter dated March 27, 2006, as supplemented by letters dated November 21, 2006, April 3, 2007, and September 12, 2007, the PWROG submitted TR WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI [Generic Safety Issue]-191," to the U.S. Nuclear Regulatory Commission (NRC) staff. By letter dated November 21, 2007, an NRC draft safety evaluation (SE) regarding our approval of WCAP-16530-NP was provided for your review and comments. By letter dated December 14, 2007, the PWROG indicated that it had no comments on the draft SE. Therefore, the NRC staff's final SE is enclosed with this letter.

The NRC staff has found that WCAP-16530-NP is acceptable for referencing in licensing applications for Westinghouse, Combustion Engineering, and Babcock and Wilcox designed pressurized water reactors to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that PWROG publish an accepted non-proprietary version of this TR within three months of receipt of this letter. The accepted version shall incorporate this letter and the enclosed final SE after the title page. Also, it must contain historical review information, including NRC requests for additional information and your responses. The accepted version shall include an "-A" (designating accepted) following the TR identification symbol.

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OG PROJECT OFFICE

G. Bischoff

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If future changes to the NRC's regulatory requirements affect the acceptability of this TR, the PWROG and/or licensees referencing it will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

Sincerely,



Ho K. Nieh, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 694

Enclosure: Final SE

cc w/encl:

Mr. James A. Gresham, Manager
Regulatory Compliance and Plant Licensing
Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230-0355
greshaja@westinghouse.com



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT WCAP-16530-NP "EVALUATION OF POST-ACCIDENT CHEMICAL

EFFECTS IN CONTAINMENT SUMP FLUIDS TO SUPPORT GSI-191"

PRESSURIZED WATER REACTOR OWNERS GROUP

PROJECT NO. 694

1.0 INTRODUCTION AND BACKGROUND

1.1 Background

By letter dated March 27, 2006 (Agencywide Documents Access Management System (ADAMS) Accession No. ML060890506), and supplemented by letters dated November 21, 2006 (ADAMS Accession No. ML063390128), April 3, 2007 (ADAMS Accession No. ML070950119), and September 12, 2007 (ADAMS Accession No. ML072570680), the Pressurized Water Reactor (PWR) Owners Group (PWROG) submitted for the U.S. Nuclear Regulatory Commission (NRC) staff review and approval the Westinghouse non-proprietary topical report (TR) WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," dated February 2006. TR WCAP-16530-NP provides an approach for plants to evaluate chemical effects that may occur in a post-accident containment sump pool.

For the purpose of this safety evaluation (SE), the issue of chemical effects involves interactions between the post-accident pressurized water reactor (PWR) containment environment and containment materials that may produce corrosion products, gelatinous material, or other chemical reaction products capable of affecting head loss across the sump strainer or components downstream of the sump strainers. This TR is applicable to PWRs only. TR WCAP-16793-NP, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous, and Chemical Debris in the Recirculating Fluid," evaluates potential chemical effects in the reactor vessel, so these effects are not addressed in TR WCAP-16530-NP nor in this SE. TR WCAP-16793-NP is being reviewed by the NRC staff and a separate SE will be provided for this report.

1.2 Introduction

In 2003, the Advisory Committee on Reactor Safeguards identified a need for an adequate technical basis to resolve concerns related to potential chemical reactions that may occur in a post-accident containment environment. Products formed from reactions between containment materials and the post-accident environment could increase head loss across the sump strainer or affect components downstream of the sump strainer. An initial scoping study was conducted by the Los Alamos National Laboratory (LANL) to evaluate potential chemical effects occurring following a loss-of-coolant accident (LOCA). This study assessed the potential for chemical products, if formed, to impede Emergency Core Cooling System (ECCS) performance (ADAMS Accession No. ML033230260). Although the LANL tests showed that gel formation with a significant accompanying head loss across a fibrous bed was possible, no integrated testing was performed to demonstrate a progression from initial exposure of metal samples to formation of chemical interaction precipitation products. In addition, the test conditions were not

intended to be prototypical of a PWR environment after a LOCA. Therefore, a more comprehensive test program was initiated to assess potential chemical effects in a more representative test environment.

An integrated chemical effects test (ICET) program was developed through a collaborative effort between the NRC staff and representatives of the nuclear industry. The test objective was to characterize any chemical reaction products, including possible gelatinous material that may develop in a representative post-LOCA PWR containment sump environment. Test conditions such as pH, temperature, and boron concentration were selected to simulate representative, but not necessarily bounding, plant conditions. The ICET series was conducted by the LANL at the University of New Mexico. Materials included in the ICET series included zinc (galvanized steel and inorganic zinc coatings), aluminum, copper, carbon steel, concrete, fiberglass, and calcium silicate insulation. Representative amounts of concrete powder, sand, and clay were also added to simulate latent debris in the containment building. Relative amounts of test materials were scaled according to plant data provided by the industry that were based on responses to a plant survey. Test coupons were either fully immersed or were placed above the test loop water line but subjected to a tank spray to simulate exposure to containment spray. The relative distributions of each material were determined based on plant estimated percentages of submerged material and material subjected to containment sprays following a LOCA.

Results from the ICET series, available in Volumes 1 to 6 of NUREG/CR-6914, "Integrated Chemical Effects Test Project" (ADAMS Accession No. ML071800338), indicated that chemical precipitates may form in representative environments. In particular, highly hydrated aluminum hydroxide and calcium phosphate precipitates were observed to form with specific combinations of plant materials and environments. The exact nature of the hydrated precipitates was difficult to characterize. Additional evaluations of aluminum hydroxide (ICET 1) type precipitates are provided in NUREG/CR-6915, "Aluminum Chemistry in a Prototypical Post-Loss-Of-Coolant-Accident Pressurized Water Reactor Containment Environment" (ADAMS Accession No. ML070160448).

Since evaluating head loss across a debris bed due to chemical precipitates was outside the scope of the ICET series, the NRC subsequently sponsored a head loss test program at the Argonne National Laboratory (ANL) to evaluate head loss effects from precipitates observed during the ICET tests. NUREG/CR-6913, "Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191" (ADAMS Accession No. ML070090553), summarizes the results of vertical loop head loss testing and bench testing. The vertical loop head loss test results at ANL showed that some of the ICET chemical products can produce significant pressure drops across a fiber bed on a flat plate test section.

A peer review of NRC-sponsored chemical effects testing was performed following the ICET tests and during the time head loss testing was being performed at ANL. Five independent peer review panel members with a diverse set of expertise raised a number of technical issues related to GSI-191 chemical effects. These issues are documented in NUREG-1861, "Peer Review of GSI-191 Chemical Effects Research Program" (ADAMS Accession No. ML063630498). The peer review panel and the NRC staff developed a phenomena identification and ranking table (PIRT) of technical issues identified by the peer review panel. The NRC staff is working to resolve those issues identified in the PIRT. Part of the resolution process includes NRC-sponsored analyses being performed by Pacific Northwest National Laboratory.

The testing and chemical models contained within TR WCAP-16530-NP are intended to provide PWR plants a methodology to perform plant-specific chemical effects evaluations. The TR WCAP-16530-NP tests were performed at higher temperatures and for shorter durations compared to ICET. Additional plant materials were included in the tests described in TR WCAP-16530-NP.

TR WCAP-16530-NP is organized into the following sections:

- Report Overview - discusses the purpose of the TR and provides a summary of the various report sections.
- Introduction - presents the background of the chemical effects issue, discusses the ICET program, and discusses the objective of the PWROG chemical effects testing in relation to ICET.
- Containment Materials - provides the results of PWR plant containment material surveys, classifies the plant materials into 5 metallic and 10 non-metallic materials, and describes the material classes.
- Test Plan - explains the bench testing purpose and approach, and provides the plans for dissolution testing and precipitation testing.
- Bench Testing - documents the bench testing performed including the functional requirements, test procedures, materials tested, and the results from the dissolution tests and precipitation tests.
- Chemical Model - presents the chemical model developed from the results of the bench testing. The chemical model is contained in a spreadsheet that predicts the type and amount of material that dissolves based on material concentrations and chemical reactions in the environment. The model also predicts the quantity and type of precipitate that forms and is intended for use to determine the amount of plant-specific precipitate that may form in a post-accident environment.
- Particulate Generator - describes the qualification testing performed on chemical precipitate that is intended to represent the precipitate performed during bench testing. This section also provides directions for making the surrogate chemical precipitate that may be used during subsequent strainer head loss testing.
- Plant-Specific Application - provides the link between the TR WCAP-16530-NP tests and strainer vendor testing using plant-specific debris, including chemical precipitates. This section also provides guidance for plant-specific application of the chemical model contained in the TR.

The NRC staff's evaluation for each of these sections is contained in Section 3.0 of this SE.

2.0 REGULATORY EVALUATION

The NRC regulations in Title 10 of the *Code of Federal Regulations* (10 CFR), Section 50.46, require that the ECCS has the capability to provide long-term cooling of the reactor core

following a LOCA. That is, the ECCS must be able to remove decay heat so that the core temperature is maintained at an acceptably low value for the extended period of time required by the long-lived radioactivity remaining in the core.

Similarly, for PWRs licensed to the General Design Criteria (GDCs) in Appendix A to 10 CFR Part 50, GDC-38 provides requirements for containment heat removal systems, and GDC-41 provides requirements for containment atmosphere cleanup. Many PWR licensees credit a containment spray system (CSS), at least in part, with performing the safety functions to satisfy these requirements, and PWRs that are not licensed to the GDCs may similarly credit a CSS to satisfy related licensing basis requirements. In addition, PWR licensees may credit a CSS with reducing the accident source term to meet the limits of 10 CFR Part 100 or 10 CFR 50.67. GDC-35 is referenced in 10 CFR 50.46(d) and specifies additional ECCS requirements. PWRs that are not licensed to the GDCs typically have similar requirements in their licensing basis.

The NRC staff's evaluation of post-accident chemical effects and TR WCAP-16530-NP is developed within the context of resolution of GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance." In order to resolve GSI-191, the NRC staff needs to have reasonable assurance that post-accident debris blockage will not impede or prevent the operation of the ECCS and CSS in recirculation mode at PWRs during LOCAs or other high-energy line break accidents for which sump recirculation is required. Following the completion of a technical assessment of GSI-191, the NRC staff issued Bulletin 2003-01, "Potential Impact of Debris Blockage on Emergency Recirculation During Design-Basis Accidents at Pressurized-Water Reactors," on June 9, 2003. As a result of the emergent issues discussed therein, the bulletin requested an expedited response from PWR licensees on the status of their compliance, on a mechanistic basis, with regulatory requirements concerning the ECCS and CSS recirculation functions. Licensees who chose not to confirm regulatory compliance were asked to describe interim compensatory measures that have been implemented to reduce risk until the analysis could be completed.

In developing Bulletin 2003-01, the NRC staff recognized that it might be necessary for licensees to undertake complex evaluations to determine whether regulatory compliance exists in light of the concerns identified in the bulletin and that the methodology needed to perform these evaluations was not currently available. As a result, that information was not requested in the bulletin, but licensees were informed that the NRC staff was preparing a generic letter that would request this information. The information was subsequently requested in GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents At Pressurized-Water Reactors" issued on September 13, 2004, included, in part, the maximum head loss postulated from debris accumulation on the submerged sump screen, including debris created by chemical precipitates that may form due to chemical reactions in the post-LOCA environment.

The NRC staff reviewed TR WCAP-16530-NP to determine whether it will provide an acceptable technical justification for the evaluation of plant-specific chemical effects, as part of the evaluations licensees are conducting to address GSI-191 concerns and to support supplemental responses to GL 2004-02.

3.0 TECHNICAL EVALUATION

3.1 Containment Materials

This section of TR WCAP-16530-NP provides a compilation of containment materials based on a survey of all 69 U.S. PWRs. This data formed the basis for selection of representative test materials and their amounts for the bench tests. Ratios of plant material to water volume were determined using the maximum amount of material and minimum water volume for each plant. Plant materials from the survey were grouped based on composition into 10 non-metallic and 5 metallic material classes. Based on results from ICET indicating no significant interactions with the environment (e.g., copper) or an analysis showing the amount of material in containment would be insignificant (e.g., organics), no tests were performed on 5 material classes. Materials were then selected from each material class for bench testing. Historical data, ICET results, and chemical similarity of the different insulation brands were used to select representative non-metallic (mineral wool, Interam, Durablanket, Nukon Fiberglass, MIN-K, Temp-Mat high density fiberglass, calcium silicate, concrete) and metal (carbon steel, galvanized steel, aluminum) samples for bench testing.

The NRC staff reviewed the selection of containment materials in the TR WCAP-16530-NP and the assumptions used to determine the materials to be tested. The materials were identified in a PWROG sponsored survey. While the NRC staff has not verified the survey results, the types and amounts of materials appear reasonable. The NRC staff questioned (Request for Additional Information (RAI) dated October 4, 2006, ADAMS Accession No. ML062440433) the TR WCAP-16530-NP assumption that the amount of RCS oxides was not significant enough to be included as a containment material in the TR tests. This NRC staff question is discussed in greater detail in Section 3.8 of this SE. The NRC also sponsored some confirmatory tests to verify the acceptability of the TR WCAP-16530-NP selections of representative materials for the various non-metallic material classes. This is discussed further in Section 3.7 of this SE.

3.2 Dissolution Testing

The objective of the dissolution tests was to determine which materials would contribute significant dissolved mass to test solutions used to represent post-LOCA containment pool conditions. Plant survey data were used to determine limits for test parameters. For example, tests were performed with pH values of 4.1, 8, and 12 to bound the postulated post-accident pH values ranging from the initial, unbuffered, low pH solution in the containment pool to the maximum postulated high pH in the CSS during sodium hydroxide injection. All test solutions contained 4400 parts per million (ppm) boron as boric acid, and this boric acid concentration produced the pH 4.1 test solution. The pH 8 and pH 12 test solutions were produced by adding sodium hydroxide to the borated water to increase the pH. Test temperatures of 190 °F and 265 °F were selected to evaluate leaching of containment materials at high temperatures simulating early initial post-accident sump conditions.

Bench tests were conducted in either Teflon or stainless steel reaction vessels that were filled to a nominal fluid volume of 120 milliliters (ml) or 150 ml, respectively. The reaction vessels were placed on a rocking platform that was located in an oven that contained the solution reservoirs and reaction chambers. Samples of the reaction vessel solutions were taken at 30, 60, and 90 minutes. The solutions were analyzed using inductively coupled plasma spectroscopy (ICP) for the elements of interest including: aluminum, calcium, silicon, magnesium, phosphorous, sulfur, iron, zinc and titanium.

The ICP results indicated that approximately 99 percent of the total mass released into solution during the leaching tests of containment materials was aluminum, silicon, and calcium. The amount of aluminum in the solution represented 75 percent of the total elemental mass released. The mass of aluminum released into solution was approximately 4 times greater than the mass of silicon released into solution and 15 times greater than the mass of calcium released into solution.

The amount of aluminum released into solution was a strong function of test solution pH. There is an order of magnitude increase in the total mass of aluminum released into solution at pH 8 relative to pH 4.1. The aluminum mass released increases by two orders of magnitude when the pH is increased from 4.1 to 12.

In terms of containment materials, aluminum, concrete, and calcium silicate released the most mass during testing. The amount of crushed concrete tested, however, was not scaled according to a representative surface area in a PWR containment since the surface area of the crushed concrete was not known prior to the start of testing. Afterwards, it was determined that the amount of concrete tested was much greater than the amount that would be representative of a U.S. PWR. The concentration of calcium due to dissolution of concrete would have been lower if the amount of concrete tested had been scaled to an upper bound of exposed concrete surface area in a PWR.

The NRC staff reviewed the test methods and results from the TR WCAP-16530-NP leaching tests and determined that the selection of pH and temperature was acceptable since the range of pH tested bounded the pH values that may be experienced by plant materials following a LOCA. The NRC staff found the TR test temperatures acceptable since greater dissolution is expected to occur at the elevated temperatures in the TR tests and this data complements the data obtained from the ICET series at 140 °F. The NRC staff found the use of ICP analysis to determine the concentration of elements that leached into solution to be acceptable since this a standard quantitative analytical method for determining the amount of a given element in solution.

3.3 Precipitation Testing

Following completion of the 90-minute leaching tests, solutions from the test reactors were transferred through a sintered stainless steel filter and small diameter stainless steel transfer lines located in a constant temperature water bath into settling cones. The water bath was maintained at 80 °F, and the solutions were visually inspected over time to look for evidence of precipitation caused by cooling the solution. In addition to the dissolution test solutions, additional precipitation test solutions were created by adding trisodium phosphate (TSP) or sodium tetraborate (STB) or by combining the solutions from different dissolution tests. More specifically, some of the pH 4.1 boric acid solutions were buffered to a pH 8 by addition of TSP or STB. In other cases, precipitation test solutions were created by combining pH 4.1 test solutions of one material (e.g., concrete) with pH 12 test solutions of a second material (e.g., aluminum).

Precipitates formed in a total of 17 experiments. Of these, 10 were single material, single test solution leaching experiments included in the precipitation test matrix. Another 2 precipitation experiments involved calcium-containing dissolution materials with subsequent additions of TSP. Mixing of solution from different leaching runs produced precipitate in 1 experiment. Finally, 4 additional experiments with single material, single test solution conditions produced precipitate.

These final 4 cases were from leaching test runs that were not included as part of the precipitation test matrix, but visual examination of the experiment detected the presence of precipitate.

Results from the leaching and precipitation tests indicated no recognizable correlation between the total amount of material in the solution during the dissolution tests and the amount of precipitate that subsequently formed during precipitation tests. The greatest volume of precipitate was formed with aluminum in a pH 12 solution. The complexity of the observed precipitation processes caused the PWROG to change the planned chemical model development such that the model does not rely on the precipitate mass measured during precipitation testing to determine the amounts of plant-specific precipitate. Instead, the model conservatively assumes all dissolved aluminum precipitates and all dissolved calcium in phosphate solutions precipitates. The TR WCAP-16530-NP also states that the precipitates formed do not settle quickly and thus cannot be discounted as a concern for sump screen performance.

Composition of the precipitates was determined by performing energy dispersive spectroscopy (EDS) on precipitate samples that were captured on filter paper and placed into a scanning electron microscope. Based on a best-estimate analysis from the EDS results, the TR concludes that the precipitates containing aluminum are predominantly aluminum oxyhydroxide and sodium aluminum silicates. EDS analysis also indicated that calcium phosphate formed in tests when dissolved calcium combined with phosphate in solution.

The NRC staff reviewed the test methods and results from the TR WCAP-16530-NP precipitation tests, and the NRC staff had some questions related these tests (see RAI dated October 4, 2006, ADAMS Accession No. ML062440433). One issue concerned whether the use of primarily single-material tests in the precipitation test matrix was appropriate considering the possibility that combined effects could result from the interaction of several materials. This issue is discussed in more detail in Section 3.8 of this SE. In addition, the NRC staff had questions concerning the limitations of the EDS technique used for the best estimate characterization of the TR WCAP-16530-NP precipitates. This issue is also discussed in greater detail in Section 3.8 of this SE. Overall, the NRC staff concluded that the use of an 80 °F water bath for cooling was appropriate since lower temperatures would typically favor the precipitation process for the aluminum-containing species, as was observed in the ICET 1 and ICET 5 tests. Post-LOCA sump pool temperatures would typically exceed 80 °F for most of the ECCS mission time.

Therefore, with the exception of those items discussed in greater detail in Section 3.8 of this SE, the NRC staff concluded that the approach to precipitation testing was acceptable.

3.4 Precipitate Filterability Tests

Precipitate filterability studies were performed to measure the filter cake coefficients of the various precipitates produced in the chemical effects bench tests. In addition, precipitate filterability tests were performed on the surrogate precipitates developed in a particulate generator and intended to represent the precipitates observed during testing. Filterability of individual precipitates was assessed by pumping the precipitate solution through a 1 micron glass fiber filter using a peristaltic pump. The solution was pumped through the filter at different flow rates and the pressure drop across the filter was determined at different flow rates. Pressure drop was plotted as a function of flow rate. This slope was then combined with the water viscosity, solids weight, and effective filter area to determine an overall filter cake coefficient.

The NRC staff questioned some of the filterability model assumptions and the conclusion that the relative filterability of the aluminum oxyhydroxide and sodium aluminum silicate surrogate precipitates was similar. For example, one of the inputs used to calculate the filter cake coefficient is precipitate mass. In these tests, precipitate mass is obtained after the test is completed by drying the hydrated precipitate that was collected on the test filter. Differences in the degree of hydration between different precipitates or between different batches of the same precipitate could introduce significant error in the calculated filter cake coefficients.

In response to the NRC staff's questions, the PWROG performed additional tests to study filterability of sodium aluminum silicate and aluminum oxyhydroxide. Some of these additional tests investigated the effects of cooling rates on precipitate properties. Based on the results from these additional tests, the PWROG concluded that the TR WCAP-16530-NP aluminum oxyhydroxide and sodium aluminum precipitates produced pressure drops equal to or greater than precipitate formed in a representative post-LOCA environment. While the NRC staff agrees that the data support the PWROG conclusions, the filterability model assumptions and the test technique used to measure filterability in the additional studies had the same fundamental weaknesses. Therefore, the NRC staff does not accept these test results to compare the relative filterability of WCAP-16530-NP precipitates. Section 3.7 of this SE discusses some NRC-sponsored testing that compares the relative filterability of TR WCAP-16530-NP precipitates. Nonetheless, it is important to note that the filterability tests in the TR were performed to permit relative comparison of the different surrogate precipitates and that these filterability test results are not factored into the chemical model predictions.

3.5 Chemical Model

Regression analysis was performed on the bench test dissolution data to develop release rate equations as a function of temperature, pH and concentration of the particular chemical species. Release rate equations were developed for each predominant containment material for each chemical species. For example, the amount of calcium released by calcium silicate insulation, concrete, and other insulation materials containing calcium are determined by different functions. Thus, bench test dissolution data are used to predict the amount of precipitate that forms and the results from precipitate analysis are used to predict the type of precipitate that forms. The model conservatively assumes all dissolved aluminum precipitates and all dissolved calcium in phosphate solutions precipitates.

Since corrosion of aluminum resulted in the greatest mass released during the TR leaching tests, the aluminum release rate incorporated into the chemical model is important. The TR contains two aluminum release rate equations that were developed by fitting different aluminum corrosion data sets, including the ICET series. The chemical model uses Equation 6-2 in the TR that was fit to a greater number of data sets. The NRC staff questioned whether Equation 6-2 provided the most appropriate aluminum release rate and whether the ICET 1 aluminum corrosion data were properly considered. The TR 16530-NP chemical model treatment of aluminum corrosion is discussed further in Section 3.7 of this SE.

The chemical model consists of a Microsoft Excel spreadsheet that contains algorithms based on the leaching and precipitation tests and uses linear sums of the individual test results to determine the total amount of material that is dissolved and precipitated. Plant-specific information is entered into the spreadsheet in several steps. The post-accident temperature and pH are entered as a function of time. The containment materials are entered into the spreadsheet according to the amounts that are submerged or wetted by containment spray. The

amount of containment material that is transported to the pool and submerged will be dependent upon the break location.

The output of the model is presented in a results table that shows the time-dependent amounts of aluminum, calcium, and silicon released. The amounts of each precipitate predicted are also provided as a function of time. Individual pages of the spreadsheet indicate the elemental release and the precipitate formation on a plant-specific material basis to allow the user to determine the potential benefits gained by reduction or removal of certain materials from their plant.

Given that the chemical model assumes all aluminum in solution and all calcium in the presence of phosphate precipitates, the NRC staff concludes that the model predictions for the amount of plant-specific precipitate are conservative and are, therefore, acceptable. The assessment of particular aspects of the model (e.g., the model's prediction of the relative amounts of surrogate precipitate) and an overall assessment of the chemical model are contained in Sections 3.7 and 3.8 of this SE.

3.6 Particulate Generator

The purpose of the particulate generator is to create surrogate chemical precipitates with representative properties that may be used during sump strainer head loss testing. Based on plant-specific inputs, the chemical model spreadsheet predicts the amount of chemical precipitates that would form in the post-accident environment. Since the precipitate filtration and settlement properties are influenced by their amorphous and hydrated nature, the particulate generator preparation is performed by mixing chemicals (e.g., water, aluminum nitrate nonahydrate, and sodium hydroxide) in solution for a minimum of an hour prior to use. The discussion in the particulate generator section of the report recognizes that representative precipitate properties may not be achieved by the use of similar chemical formula solid material. The NRC staff agrees that pre-manufactured particulate, e.g., calcium phosphate powder, behaves differently than hydrated, amorphous, precipitate that was observed during the ICET series. Therefore, the NRC staff does not consider addition of commercially manufactured particulate with similar chemical composition to be an adequate simulation of chemical precipitates.

During particulate generator qualification testing, the effects of precipitate concentration in the mixing tank were evaluated, and it was observed that precipitate solutions prepared at higher mixing tank concentrations settled at atypically high rates, even after subsequent dilution. Figures 7.6-1 and 7.6-2 in TR WCAP-16530-NP show the effect of mixing tank concentration on the settling rates of aluminum oxyhydroxide and calcium phosphate, respectively. The results shown in these figures, that high concentrations favor formation of precipitate with faster settling properties, is consistent with earlier test observations concerning precipitate concentration effects on settling properties at ANL (NUREG/CR-6913). Therefore, TR WCAP-16530-NP states that the maximum concentrations of aluminum oxyhydroxide and sodium aluminum silicate in the mix tank should not exceed 11 grams per liter. The maximum mix tank concentration for the calcium phosphate precipitate should not exceed 5 grams per liter.

In addition to the mixing tank concentration limits, TR WCAP-16530-NP provides maximum acceptable 1-hour precipitate settlement values to preclude atypical settling of the surrogate precipitate. The acceptable precipitate 1-hour settled volume criteria, shown in Table 7.8-1 of the TR, is greater than 4 ml for all three surrogate precipitates. In other words, when starting

cloudy after one hour. Although the NRC staff understands that precipitate will settle slower during screen vendor testing due to bulk directional flow, the NRC staff questioned if the above settling criteria were adequate given the observations of slow precipitate settling reported in Table 5.3-1 in the topical report. The NRC staff position on acceptable precipitate settling criteria is discussed in Section 3.8 of this SE.

The NRC staff questioned whether the 1-hour settled volume criterion was sufficient for two reasons. First, a batch of aluminum oxyhydroxide prepared for head loss testing displayed a distinct change in properties over time even though the 1-hour settlement values met the acceptance criteria. Second, a modified strainer head loss testing approach, with the objective of settling all debris including chemical precipitate, was proposed by some licensees. This test approach is very different from an approach that intentionally uses agitation to keep chemical precipitate suspended to ensure it reaches the test strainer.

To address this shortcoming, the NRC staff reviewed the results from precipitate settling in the TR WCAP-16530-NP, specifically Figures 7.6-1 and 7.6-2 and Table 5.3-1, and results from other settling tests at ANL. The NRC staff also included a time-dependent criterion for settlement testing relative to head loss testing to preclude precipitate aging from significantly changing the surrogate precipitate properties before it is used. The NRC staff finds the following proposed modification (ADAMS Accession No. ML072570680) to the settling rates in TR WCAP-16530-NP to be acceptable:

1. For head loss tests in which the objective is to keep chemical precipitate suspended (e.g., by tank agitation):

Sodium aluminum silicate and aluminum oxyhydroxide precipitate settling shall be measured within 24 hours of the time the surrogate will be used and the 1-hour settled volume (for an initial 10 ml solution volume) shall be 6 ml or greater and within 1.5 ml of the freshly prepared surrogate. Calcium phosphate precipitate settling shall be measured within 24 hours of the time the surrogate will be used and the 1-hour settled volume shall be 5 ml or greater and within 1.5 ml of the freshly prepared surrogate. Testing shall be conducted such that the surrogate precipitate is introduced in a way to ensure transport of all material to the test screen.

2. For head loss testing in which the objective is to settle chemical precipitate and other debris:

Aluminum-containing surrogate precipitate that settles equal to or less than the 2.2 g/l concentration line shown in Figure 7.6-1 of WCAP-16530-NP (i.e., 1-hour or 2-hour settlement data on or above the line) is acceptable. The settling rate should be measured within 24 hours of the time the surrogate precipitate will be used.

For testing that was performed prior to the time the PWROG notified licensees of a revised precipitate settlement acceptance criteria, licensees should evaluate the precipitate settlement of these tests considering the observations provided in the response to NRC comment 7 provided in PWROG letter dated September 12, 2007 (ADAMS Accession No. ML072570680).

3.7 NRC-Sponsored Confirmatory Testing

During the NRC staff's review of TR WCAP-16530-NP, the NRC staff determined that some confirmatory testing was necessary in order to independently assess certain aspects of TR WCAP-16530-NP. In general, the NRC staff was interested in: (1) supplementary and confirmatory dissolution and precipitation experiments for insulation materials and concrete, and (2) testing to evaluate the properties of surrogate precipitates prepared using the instructions provided for the particulate generator in the TR. Therefore, the NRC staff sponsored additional dissolution and precipitation testing at the Southwest Research Institute (SwRI). In addition, the NRC sponsored bench testing and head loss testing of TR WCAP-16530-NP chemical surrogate at ANL.

The main purpose of the supplementary leaching studies performed at SwRI was to examine the validity of the assumption in the TR that various non-metallic materials in the same class would exhibit similar dissolution characteristics. A secondary objective was to characterize any precipitate that formed. For the SwRI tests, five materials that had not been tested by the PWROG were selected from various insulation classes to determine if the material tested by the PWROG was representative of other materials in the same class. The SwRI test matrix included E-glass materials (fiberglass, Alpha-Mat™, Temp-Mat A™), amorphous silica (Microtherm™), calcium silicate (Marinite™), and aluminum silicate (Kaowool™). The test conditions were selected by focusing on the test conditions that had provided the most concentrated leachate solutions for each material class. Since the testing apparatus and procedures were similar but not identical to that used for the topical report tests, some previously tested materials (calcium silicate, Fiber Frax™, Durablanket™, and concrete) were also included to allow comparison between the TR test results and the SwRI test results. Details of the test conditions and the test results are provided in a SwRI letter report, "Supplementary Leaching Tests of Insulation and Concrete for GSI-191 Chemical Effects Program" (ADAMS Accession No. ML063330573).

For leaching tests with similar times, temperatures, and pH, the concentration of elements in the SwRI leaching tests were similar to or less than the concentrations from the TR tests. With the exception of calcium silicate in certain test conditions, SwRI tests of the same insulation resulted in lower elemental concentrations in solution compared to the TR tests. Significantly less silicon leached from the fiberglass samples during the SwRI tests. The amount of calcium leached from concrete was also lower in the SwRI tests, which was expected since the SwRI tests used a concrete coupon with a scaled surface area representing the upper plant bound for uncoated concrete. The TR WCAP-16530-NP tests used an amount of crushed concrete that exceeded plant levels (see Section 3.2 of this evaluation).

No precipitates were observed to settle in any of the SwRI tests even when using the same materials and same test conditions that produced precipitates in the TR WCAP-16530-NP tests. Although the test conditions were similar, there were a few differences between the SwRI and the TR test techniques that could have affected the results. For instance, the SwRI test solutions were cooled over a 2-hour period during which time the test material remained in contact with the test solution. In contrast, the TR test solution was immediately filtered and transferred to the precipitation settling cones in the cooling water bath at the completion of the dissolution test period. Therefore, the SwRI test materials remained in contact with solution for a significantly longer period, and the SwRI test solution was cooled at a significantly slower rate compared to the TR test solution. The longer time for dissolution in the SwRI tests would promote greater dissolution. This is offset by the greater agitation for the TR tests, where the individual reaction vessels were placed on a rocking platform in the test oven. The slower

cooling rates in the SwRI tests would be more similar to the fluid cooling of the containment sump pool following a LOCA. The more rapid cooling in the TR tests may be more similar to cooling that would occur as fluid from the sump passes through a residual heat removal (RHR) heat exchanger. The TR test solution cooling would not be prototypical of cooling in an ECCS system, however, since fluid that passes from the sump through a RHR heat exchanger would be reheated as it passes into the reactor vessel or spills out a break and returns to the post-LOCA pool on the containment floor. This effect would increase the solubility of some precipitates since reheating may cause the precipitates to go back into solution.

Overall, results from the SwRI dissolution and precipitation tests did not contradict the TR WCAP-16530-NP assumptions concerning leaching from representative materials in different classes. In addition, no precipitates were formed with the new test materials. Therefore, the NRC staff finds the TR classification of materials and the selection of representative test materials to be acceptable.

While the NRC-sponsored tests at SwRI were intended to verify some of the TR assumptions related to representative materials and to repeat some of the dissolution and precipitation tests, the goal of NRC-sponsored tests at ANL was to evaluate the surrogate chemical precipitate prepared using the instructions in the TR. Tests at ANL included bench testing to study the TR precipitate characteristics and vertical loop head loss testing to evaluate the head loss properties of the precipitate (see ANL Technical Letter Report, ADAMS Accession No. ML070580086). These tests focused on the aluminum oxyhydroxide and sodium aluminum silicate precipitates since these are the predominant precipitates predicted by the TR chemical model and ANL had previously performed extensive testing with the calcium phosphate precipitate, as reported in NUREG/CR-6913.

The TR procedure for preparing surrogate chemical precipitate recognizes that the precipitate concentration in the mixing tank will affect the size and settling properties of the precipitate. Therefore, the procedure limits the maximum concentration of the mixing tank and provides criteria for acceptable one-hour settling volumes. ANL evaluated precipitates prepared according to the TR instructions and also prepared precipitates by deviating from the TR guidelines to evaluate the potential effects on the precipitate properties. Overall, the TR precipitate preparation specifications seem effective at producing fine precipitate that is most probably finely crystalline, although no clear diffraction pattern was obtained due to the small particle size. Bench testing also showed that precipitate settling rates were slower for aluminum oxyhydroxide precipitate produced according to the TR directions. X-ray diffraction of the precipitates prepared outside the bounds of the TR instructions indicated a crystalline structure (bayerite). This precipitate, however, did not meet the TR settlement acceptance criteria.

ANL also conducted vertical head loss loop tests of the aluminum oxyhydroxide and sodium aluminum silicate precipitates to evaluate their filterability. The NRC staff was interested in evaluating the relative filterability of these two precipitates since the TR chemical model predictions assume, based on thermodynamic equilibrium predictions, that sodium aluminum silicate precipitate will form before aluminum oxyhydroxide precipitate if sufficient silicate is present. Although the chemical model conservatively assumes that all aluminum in solution precipitates, based on the information provided in the TR, the NRC staff was not able to conclude that the model predictions for the relative amounts of aluminum oxyhydroxide and sodium aluminum silicate that form are accurate. Therefore, the NRC staff sponsored head loss testing at ANL to compare the relative filterability of sodium aluminum silicate and aluminum oxyhydroxide precipitates.

In these tests, a standard fiberglass debris bed was formed using NUKON fiberglass fibers that had been shredded and processed in a blender to produce individual fibers. A fiberglass debris bed was formed and a baseline pressure drop was measured before addition of surrogate precipitate. The first test used the TR aluminum oxyhydroxide precipitate in an amount equivalent to what would be produced if 5 parts per million (ppm) of dissolved aluminum from the 119-liter vertical head loss loop volume were to transform into precipitate. This amount of TR precipitate resulted in a rapid increase in pressure drop across the fiber-covered screen, and the pressure drop capacity of the test loop was exhausted almost immediately.

Given the rapid increase in pressure drop with the initial test of the TR aluminum oxyhydroxide precipitate, an additional head loss test with this precipitate was performed using smaller incremental additions, equivalent to 0.5 ppm of dissolved aluminum in the test loop transforming into precipitate. Using these reduced precipitate additions, the system's pressure drop capacity was exceeded with a total addition equivalent to 1.5 ppm of dissolved aluminum in the loop transforming to precipitate.

ANL also performed vertical loop head loss testing with the TR sodium aluminum silicate precipitate. An initial head loss test in deionized water revealed that the sodium aluminum silicate precipitate was dissolving over time. Small additions of precipitate would produce an initial increase in pressure drop comparable to the aluminum oxyhydroxide precipitate, however, the pressure drop would decrease over time. After adding an amount of aluminum equivalent to 5 ppm of dissolved aluminum in the vertical loop transforming into sodium aluminum silicate precipitate, the head loss was near the loop capacity but still exhibited the pressure drop decay behavior over time. Subsequent bench testing with deionized and potable water indicated that approximately 2 ppm of sodium aluminum silicate dissolves in deionized water and that the pH of deionized water becomes more alkaline compared to potable water for a given amount of sodium aluminum silicate addition. Therefore, if deionized water were to be used for strainer head loss testing, the solubility of sodium aluminum silicate shall be accounted for when determining the appropriate amount to be added to the test.

Since strainer vendors that add TR surrogate precipitate to larger scale integrated head loss tests use potable water, not deionized water, a second sodium aluminum silicate head loss test was conducted with potable water in the vertical head loss test loop. With potable water, the system's pressure drop capacity was exceeded with a total sodium aluminum silicate addition equivalent to 2.2 ppm of dissolved aluminum in the loop transforming to precipitate. In addition, the pressure drop across the debris bed remained stable for greater than 10 hours after an equivalent 2 ppm of dissolved aluminum as sodium aluminum silicate was introduced. Although there were some small differences in the vertical loop head loss test results, the vertical loop test results indicate that small quantities of both these TR surrogate precipitates are effective at causing significant pressure drop across a fiber bed.

3.8 Overall Staff Technical Evaluation

There are a number of different technical issues embedded within the TR WCAP-16530-NP methodology. In this section, the NRC staff discusses important technical issues and provides an overall staff evaluation of TR WCAP-16530-NP.

Role of RCS Oxides

One of the potential material source terms that was judged to be insignificant in TR WCAP-16530-NP is potential reactor coolant system (RCS) oxides released during a LOCA. In letters dated October 4, 2006, and March 23, 2007 (ADAMS Accession Nos. ML062440433 and ML070810208), the NRC staff requested additional information from the PWROG related to the amount of RCS oxides that could be released during a LOCA and the potential effects of these oxides on chemical effects. In letters dated November 21, 2006, April 3, 2007, and September 12, 2007 (ADAMS Accession Nos. ML063390128, ML070950119, and ML072570680), the PWROG provided information supporting its conclusion that the amount of crud released during a LOCA would be insignificant compared to the other debris that is included in strainer head loss testing. Based on the additional information provided in the RAI responses, conservatism in other parts of the chemical model (e.g., all aluminum in solution precipitates), and considering the amounts of other particulate debris included in strainer testing, the NRC staff finds that the amounts and effects of RCS oxides can be considered insignificant for strainer head loss testing. Therefore, the NRC staff concludes that it is acceptable that RCS oxides are not included in the TR WCAP-16530-NP head loss testing source term.

Aluminum Release Rates

Corrosion of aluminum resulted in the greatest mass released during the TR WCAP-16530-NP dissolution tests. Therefore, the aluminum release rate incorporated into the chemical model is important. The aluminum release rate was determined by considering a number of test results, including the ICET series. The fit to the ICET data is based on an average 30-day aluminum corrosion rate, but measurement of aluminum in solution during the ICET 1 test indicated an active phase of aluminum corrosion during the initial half of the test followed by aluminum passivation during the second half of the test. By using an averaged value, the TR chemical model release rate under-predicts aluminum release by about a factor of 2 for the active corrosion part of ICET 1. The NRC staff finds this acceptable since licensees using the TR WCAP-16530-NP surrogate precipitate typically add the amount predicted for a 30-day mission time while using a first-day pump net positive suction head (NPSH) margin acceptance criteria. If a licensee performs strainer head loss tests with TR WCAP-16530-NP surrogate precipitate and applies a time-based pump NPSH margin acceptance criteria (i.e., timed precipitate additions based on TR model predictions), the NRC staff expects the licensee to use an aluminum release rate that does not under-predict the aluminum concentrations during the initial 15 days of ICET 1. In this case, aluminum passivation may be considered during the latter parts of the ECCS mission time.

Identification of Precipitate Types

Amorphous, hydrated precipitates, such as those that formed in ICET and those that appeared to form in the TR WCAP-16530-NP tests, are difficult to characterize. Some of these precipitates, such as the aluminum hydroxide type precipitates, may initially form as an amorphous material and then change into a crystalline structure over time as a result of an aging process. The EDS technique used to analyze the precipitates that formed during the TR WCAP-16530-NP tests is not definitive, and the EDS analysis was not sensitive to either boron or carbon that may have been contained in the precipitate. The NRC staff notes that TR WCAP-16530-NP aluminum oxyhydroxide surrogate

precipitate is prepared by adding aluminum nitrate to water followed by sodium hydroxide. This results in formation of precipitate at a lower pH compared to a post-LOCA environment where this type of precipitate would most probably form after the pH was greater than 7. The NRC staff cannot conclude that the TR WCAP-16530-NP surrogate precipitates are identical to those that formed in ICET and in the TR tests, because of (1) the limitations in the EDS technique used to identify the TR WCAP-16530-NP precipitates, (2) the fact that prediction of sodium aluminum silicate precipitate formation in the TR is somewhat based on thermodynamic calculations, and (3) the surrogate precipitate preparation sequence that adds aluminum nitrate before adjusting the pH with sodium hydroxide. Nevertheless, the technical approach used in the TR WCAP-16530-NP does not rely on making the exact precipitates that formed during testing but rather surrogate precipitates that have representative properties such as precipitate settlement and filterability. Therefore, the NRC staff review focused on determining if the predicted types, filterability, and amount of surrogate precipitates were either representative or conservative when compared to those precipitates that may form in the post-LOCA plant environment. Based on its review, the NRC staff concludes that the surrogate precipitate that is prepared in accordance with the TR WCAP-16530-NP directions provides adequate settlement and filterability characteristics to represent post-LOCA chemical precipitates in strainer head loss tests.

Amount of Precipitate

With respect to the total amount of precipitate, TR WCAP-16530-NP assumes all dissolved calcium, in the presence of phosphate, and all dissolved aluminum form precipitates. This is a reasonable assumption for calcium dissolved in a TSP-buffered solution, since a calcium phosphate precipitate forms and calcium, not phosphate, is expected to be the limiting reactant. The assumption that all dissolved aluminum forms a precipitate is clearly a conservative assumption when compared to literature values and measured values of dissolved aluminum in alkaline, borated test solutions at LANL and ANL. The solubility of aluminum is dependent on the temperature and the pH of the sump pool following a LOCA. One indication that not all dissolved aluminum precipitates is shown by the room temperature (49 mg/L) concentration of aluminum in the ICET 1 test fluid supernate four months after the completion of the test. However, this value should not be assumed to be a solubility limit since sub-micron suspended aluminum hydroxide particles that are not visible have been shown to cause head loss in tests at ANL. The NRC staff concludes that the chemical model prediction on the total amount of precipitate, i.e., that all dissolved aluminum precipitates, is acceptable since this results in a conservative amount of precipitate.

Single Effects vs. Multiple Material Tests

Dissolution and precipitation evaluations in the TR WCAP-16530-NP are based mostly on single-effects testing. Although single-effects testing complements the ICET tests and may produce conservative amounts of dissolved materials in some instances, this testing approach could miss some important combined effects from multiple materials. Combined effects may or may not be conservative relative to projections from separate effects testing. For example, silicates are known to inhibit aluminum corrosion. The chemical model in TR WCAP-16530-NP may significantly over-predict the amount of silica released from fiberglass since the TR WCAP-16530-NP tests did not consider the potential effects of dissolved aluminum inhibiting leaching of silica from fiberglass.

Therefore, TR WCAP-16530-NP may be conservative in some plant-specific environments with respect to the amount of silica leaching from fiberglass, but non-conservative if the predicted pool silica levels are then used in an attempt to credit passivation of aluminum. Although single effects testing results in greater uncertainty compared to integrated testing, the NRC staff finds this acceptable since other conservative assumptions in the chemical model offset uncertainties associated with single effects tests. Examples of those assumptions include: (1) all aluminum that goes into solution forms a precipitate, (2) the topical report takes no credit for phosphate inhibition of aluminum corrosion in TSP environments, and (3) the topical report takes no credit for inhibition of aluminum corrosion by silicates. In addition, test results from the ICET series and some limited long-term tests with representative post-LOCA temperatures and pH values have shown that the TR WCAP-16530-NP chemical model does not under-predict chemical precipitates.

Form of Aluminum Precipitates

TR WCAP-16530-NP surrogate precipitate composition is based on "best estimate" analysis of precipitate formed during bench testing. As previously mentioned in Section 3.6 of this SE, the NRC staff questioned the model's ability to accurately predict the relative amounts of aluminum oxyhydroxide and sodium aluminum silicate precipitates that could form in a plant-specific environment. The NRC-sponsored head loss tests at ANL were designed to compare the head loss test results of aluminum precipitating as an aluminum hydroxide to aluminum precipitating as a sodium aluminum silicate. The tests at ANL confirmed that small quantities of each TR surrogate precipitate produced significant pressure drop across a Nukon fiber bed. Therefore, even though the NRC staff cannot conclude that the model predictions for relative amounts of aluminum hydroxide and sodium aluminum silicate are accurate, the ANL tests have shown that the effects of the two surrogate precipitates are similar. Therefore, the NRC staff finds the TR WCAP-16530-NP predicted amount of precipitate to be acceptable since all aluminum is assumed to precipitate and small quantities of each precipitate are effective at producing significant head loss across a fiber bed.

Precipitate Settlement Criteria

Precipitate settlement is another important surrogate precipitate characteristic that was reviewed by the NRC staff. Precipitate that formed during cooling of ICET solutions and during the TR WCAP-16530-NP bench tests was observed to settle slowly. During the surrogate precipitate development stage, TR WCAP-16530-NP tests showed that the surrogate precipitate mixing tank concentration affected the settling properties. Therefore, TR WCAP-16530-NP recommends a maximum mixing concentration to achieve reasonably prototypical settling behavior. In addition, TR WCAP-16530-NP provides criteria for physical characteristics of acceptable surrogate precipitates, including criteria for a 1-hour settled volume. As a condition on the use of this TR, licensees must implement the additional settlement criteria described in response to NRC comment 7 of the September 12, 2007 letter (ADAMS Accession ML072570680), for proper use of the surrogate precipitate materials. These criteria are provided in Section 4.0 of this SE.

Based on the considerations above, although there are uncertainties associated with the actual formation of chemical products in a post-LOCA plant environment, the NRC staff finds the

overall technical approach in TR WCAP-16530-NP to be acceptable for plant-specific chemical effect evaluations since this approach predicts a conservative amount of chemical precipitate and the surrogate precipitate filterability is either representative or conservative compared to precipitate that may be expected to form in a post-LOCA environment.

4.0 LIMITATIONS AND CONDITIONS

1. A peer review of NRC-sponsored chemical effects testing was performed and a number of technical issues related to GSI-191 chemical effects were raised by the independent peer review panel members (NUREG-1861). The peer review panel and the NRC staff developed a PIRT of technical issues identified by the peer review panel. The NRC staff is working to resolve the technical issues identified in the PIRT. Part of the resolution process includes NRC-sponsored analyses being performed by PNNL. Although the NRC staff has not developed any information related to the PIRT issues resolution that would alter the conclusions of this evaluation, some issues raised by the peer review panel were not completely resolved at the time this evaluation was written. An example of such an issue is the potential influences of organic materials on chemical effects. Therefore, it is possible that additional analysis or other results obtained during the resolution of the remaining peer review panel issues could affect the conclusions in this evaluation. In that event, the NRC staff may modify the SE or take other actions as necessary.
2. This evaluation does not address TR WCAP-16785-NP, "Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model." The NRC staff will provide comments on WCAP-16785-NP separate from this evaluation. In addition, a separate SE will address a related TR, WCAP-16793-NP, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous, and Chemical Debris in the Recirculating Fluid." Chemical effects in the reactor vessel are not addressed in WCAP-16530-NP or in this SE. Therefore, the approval of this TR does not extend to chemical effects in the reactor vessels.
3. If a licensee performs strainer head loss tests with surrogate precipitate and applies a time-based pump NPSH margin acceptance criteria (i.e., timed precipitate additions based on topical report model predictions), they must use an aluminum release rate that does not under-predict the initial 15 day aluminum concentrations in ICET 1, although aluminum passivation can be considered during the latter parts of the ECCS mission time in this case.
4. For head loss tests in which the objective is to keep chemical precipitate suspended (e.g., by tank agitation):

Sodium aluminum silicate and aluminum oxyhydroxide precipitate settling shall be measured within 24 hours of the time the surrogate will be used and the 1-hour settled volume shall be 6 ml or greater and within 1.5 ml of the freshly prepared surrogate. Calcium phosphate precipitate settling shall be measured within 24 hours of the time the surrogate will be used and the 1 hour settled volume shall be 5 ml or greater and within 1.5 ml of the freshly prepared surrogate. Testing shall be conducted such that the surrogate precipitate is introduced in a way to ensure transportation of all material to the test screen.

5. For head loss testing in which the objective is to settle chemical precipitate and other debris:

Aluminum containing surrogate precipitate that settles equal to or less than the 2.2 g/l concentration line shown in Figure 7.6-1 of WCAP-16530-NP (i.e., 1-or 2-hour settlement data on or above the line) is acceptable. The settling rate shall be measured within 24 hours of the time the surrogate precipitate will be used.

6. For strainer head loss testing that uses TR WCAP-16530-NP sodium aluminum silicate and is performed in a de-ionized water environment, the total amount of sodium aluminum silicate added to the test shall account for the solubility of sodium aluminum silicate in this environment.

5.0 CONCLUSION

The NRC staff has reviewed WCAP-16530-NP and the supplemental information that was transmitted by letters dated November 21, 2006, April 3, 2007, and September 12, 2007, and has found that the TR, as modified and clarified to incorporate the NRC staff's recommendations, and subject to the conditions and limitations in Section 4.0 of this SE, provides an acceptable technical justification for the evaluation of plant specific chemical effects related to GSI-191. The supplemental information that was provided in response to the NRC staff's RAIs shall be incorporated into the approved version of TR WCAP-16530-NP. In addition, where this SE states that a change to the TR is needed, such changes shall also be incorporated in the approved version.

6.0 REFERENCES

1. PWROG Letter WOG-06-113, "Submittal of WCAP-16530-NP, 'Evaluation of Post Accident Chemical Effects in Containment Sump Fluids to Support GSI-191' for Formal Review," dated March 27, 2006 (ADAMS Accession No. ML060890506).
2. WCAP-16530-NP, Revision 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," dated February 2006 (ADAMS Accession No. ML060890509).
3. NRC Letter to PWR Owners Group, "Request For Additional Information Re: Westinghouse Owners Group Topical Report WCAP-16530-NP, Evaluation of Post Accident Chemical Effects in Containment Sump Fluids To Support GSI-191," dated October 4, 2006 (ADAMS Accession No. ML062440433).
4. PWROG Letter OG-06-387, "Responses to NRC Request For Additional Information (RAI) on WCAP-16530, 'Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191,'" dated November 21, 2006 (ADAMS Accession No. ML063390128).
5. NRC Letter to PWR Owners Group, "Request For Additional Information Re: Westinghouse Owners Group Topical Report WCAP-16530-NP, Evaluation of Post Accident Chemical Effects in Containment Sump Fluids To Support GSI-191," dated March 23, 2007 (ADAMS Accession No. ML070810208).

6. PWROG Letter OG-07-129, "Responses to the Second Set of NRC Requests For Additional Information (RAI) on WCAP-16530, Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," dated April 3, 2007 (ADAMS Accession No. ML070950119).
7. PWROG Letter OG-07-408, "Responses to NRC Requests For Clarification Regarding WCAP-16530, Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," (PA-SEE-0275), dated September 12, 2007 (ADAMS Accession No. ML072570680).
8. Los Alamos National Laboratory Report LA-UR-03-6415, "Small Scale Experiments: Effects Of Chemical Reactions On Debris Bed Head Loss," dated November 2003 (ADAMS Accession No. ML0033230260).
9. NUREG/CR-6914, "Integrated Chemical Effects Test Project: Consolidated Data Report," dated December 2006 (ADAMS Accession No. ML071800338).
10. NUREG/CR-6915, "Aluminum Chemistry in a Prototypical Post-Loss-Of-Coolant-Accident Pressurized Water Reactor Containment Environment, dated December 2006 (ADAMS Accession No. ML070160448).
11. NUREG/CR-6913, "Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191," dated December 2006 (ADAMS Accession No. ML070090553).
12. NUREG-1861, "Peer Review of GSI-191 Chemical Effects Research Program," dated December 2006 (Accession No. ML063630498).
13. Southwest Research Institute Letter Report IM20.12130.01.001, "Supplementary Leaching Tests of Insulation and Concrete For GSI-191 Chemical Effects Program," dated November 2006 (ADAMS Accession No. ML063330573).
14. Argonne National Laboratory Technical Letter Report "Follow-On Studies in Chemical Effects Head Loss Research; Studies of WCAP Surrogate and Sodium Tetraborate Solutions," dated February 15, 2007 (ADAMS Accession No. ML070580086)

Principle Contributor: Paul Klein

Date: December 21, 2007

SECTION B



Domestic Members

AmerenUE
Callaway
American Electric Power Co.
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Arizona Public Service Co.
Palo Verde 1, 2 & 3
Constellation Energy Group
Calvert Cliffs 1 & 2
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Dominion Kewaunee
Dominion Nuclear Connecticut
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Dominion Virginia Power
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Wolf Creek Nuclear Operating Corp.
Wolf Creek

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Korea Hydro & Nuclear Power Co.
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Ulchin 3 - 6
Yonggwang 1 - 6
NEK
Krško
NOK
Kernkraftwerk Boznau
Ringhals AB
Ringhals 2 – 4
Spanish Utilities
Asco 1 & 2
Vandellós 2
Almaraz 1 & 2
Taiwan Power Co.
Maanshan 1 & 2

Project Number 694

WOG-06-113

March 27, 2006

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Mr. Jesse L. Funches
Chief Financial Officer
U.S. Nuclear Regulatory Commission
One White Flint North – Mail Code O-17F3
11555 Rockville Pike
Rockville, MD 20852-2738

Subject: Submittal of WCAP-16530-NP, “Evaluation of Post Accident Chemical Effects in Containment Sump Fluids to Support GSI-191” for Formal Review

The PWR Owners Group has commissioned WCAP-16530-NP, Revision 0, “Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191,” to provide a consistent approach for plants to evaluate the chemical effects which may occur post-accident in containment sump fluids. The results of this evaluation are intended to provide input on the type and amounts of chemical precipitates which may form post-accident for testing of replacement sump screens. The overall issue is being driven by Generic Safety Issue (GSI) 191 and the subsequent NRC Generic Letter (GL) 2004-02.

In response to a request for the informal submittal of the report from the Nuclear Regulatory Commission (NRC) during the February 9, 2006 Public Meeting, the PWR Owners Group is providing WCAP-16530-NP for formal review to the NRC. The PWR Owners Group believes an informal submittal would be inappropriate for such an important issue as GSI-191, and as such, believes that both the NRC and industry’s interests will be best served by a formal review of WCAP-16530-NP.

This letter transmits four (4) copies of WCAP-16530-NP Revision 0, dated February 2006 and errata letter WOG-06-107. The PWR Owners Group is submitting WCAP-16530-NP Revision 0 in accordance with the Nuclear Regulatory Commission (NRC) licensing topical report program for review and acceptance for referencing in licensing actions. This topical report is being provided for formal review and at the request of the NRC.

Formal documentation of any questions or comments on this subject report is requested through the NRC's Request for Additional Information (RAI) process. Consistent with the Office of Nuclear Reactor Regulation, Office Instruction LIC-500, "Processing Request for Reviews of Topical Reports," the PWR Owners Group requests that the NRC provide target dates for any Request(s) for Additional Information and for issuance of the Safety Evaluation. Correspondence related to this transmittal and invoices associated with the review of WCAP-16530-NP, Revision 0, should be addressed to:

Mr. Gordon Bischoff
Manager, Owners Group Program Management Office
Westinghouse Electric Company
Mail Stop ECE 5-16
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355

The PWR Owners Group requests that a fee waiver be considered for the NRC review of WCAP-16530-NP pursuant to the provisions of 10 CFR 170.11(a)(1)(i). WCAP-16530-NP provides technical background as requested by the NRC in the Safety Evaluation of NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology." Both NEI-04-07, which was exempt from NRC review fees, and WCAP-16530-NP were developed in response to NRC request associated with Generic Safety Issue GSI-191. The application of the methods and information described in this report will reduce regulatory burden and allow for more appropriate allocation of NRC inspection resources.

If you have any questions, please do not hesitate to contact me at 630-657-3897 or Mr. Gordon Bischoff of the Owners Group Program Management Office at 860-731-6200. If you require further information, please contact Mr. Reginald R. Dulaney in the PWR Owners Group Program Management Office at 412-374-6549.

Regards,

Reginald Dulaney approving for T. Schiffley
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Frederick P. "Ted" Schiffley, II, Chairman
PWR Owners Group

mjl

Enclosure

cc: WOG Steering Committee
WOG Management Committee
WOG Licensing Subcommittee
WOG Systems and Equipment Engineering Subcommittee
PWR Owners Group Program Management Office
G. Shukla, USNRC
B. Gramm, USNRC
J. Butler, NEI
T. S. Andreychek, Westinghouse
P. V. Pyle, Westinghouse
R. W. Rinkacs, Westinghouse
K. J. Vavrek, Westinghouse
J. Bass, Westinghouse
L. I. Ezekoye, Westinghouse
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Member Participation* for PWROG Project Authorization PA-SEE-0275

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American Electric Power	D.C. Cook 1&2 (W)	X	
Arizona Public Service	Palo Verde Unit 1, 2, & 3 (CE)	X	
Constellation Energy Group	Calvert Cliffs 1 & 2 (CE)	X	
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*** - This is a list of participants in this project as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWROG Management Office to verify participation before sending documents to participants not listed above.**

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Utility Member	Plant Site(s)	Participant	
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EXECUTIVE SUMMARY

The Pressurized Water Reactor Owners Group (PWROG) has commissioned this report to provide a consistent approach for plants to evaluate the chemical effects which may occur post-accident in containment sump fluids. The results of this evaluation are intended to provide input on the type and amounts of chemical precipitates which may form post-accident for testing of replacement sump screens. The overall issue is being driven by Generic Safety Issue (GSI) 191 and the subsequent Nuclear Regulatory Commission (NRC) Generic Letter (GL) 2004-02.

Each plant, given their plant-specific containment material concentrations, pH, and temperature post-accident, can use the enclosed information to determine the type and amounts of chemical precipitates which may form and be transported to the sump screen. In order to meet this purpose, the report discusses the following:

- Containment materials
- Rate of dissolution of materials
- Precipitate formation due to cooling and chemical reactions
- Development of a chemical model to predict dissolution and precipitate formation
- Use of particulate generator to produce representative precipitates for screen testing

Specifically, the report presents the following conclusions.

Containment Materials

The containment materials provided on the plant surveys can be divided into fifteen (15) material classes based on their chemical composition. Ten (10) of these material classes were determined to have the potential to cause chemical effects in the containment sump: aluminum, aluminum silicate, calcium silicate, carbon steel, concrete, E-glass, amorphous silica, Interam E class, mineral wool, and zinc. The basis for excluding the remaining five (5) material classes is included in Section 3.2.

Dissolution Testing

Bench testing was performed on representative containment materials from the classes above to evaluate the dissolution characteristics of these materials. Samples were taken of the dissolved solution and were analyzed for the presence of aluminum (Al), calcium (Ca), silicon (Si), magnesium (Mg), phosphorus (P), sulfur (S), iron (Fe), zinc (Zn), and titanium (Ti). The dissolved mass values obtained for the elements P, Mg, and Ti were negligible, so these elements were not considered in precipitation formation. The elements having the highest concentration were aluminum, silicon, and calcium, and these elements are the most likely to form precipitates.

Precipitation Testing

Precipitate formed in thirteen of the sixty precipitation tests performed. In 10 tests, precipitates formed after containment materials were exposed to simulated coolant and after the temperature of the coolant was reduced. The dissolved solution from the aluminum starting material formed aluminum oxyhydroxide precipitate upon cooling for the three pH values tested. The Fiber Frax, galvanized steel, and untested fiberglass at a pH of 12 formed precipitates. For a solution pH of 4, the concrete, mineral wool, and Fiber Frax formed precipitate

upon cooling. The concrete also formed precipitate at a pH of 8. These precipitates were predominately aluminum oxyhydroxide and either calcium aluminum silicate or sodium aluminum silicate. The materials tested which did not form noticeable amounts of precipitate upon cooling were carbon steel, NUKON fiberglass, Min-K, and Interam.

Precipitation occurred upon cooling of the coolant solution because the solubility of the solids precipitating from solution decreased with decreasing temperature. The solutions became supersaturated, and crystals of that phase nucleated and grew after a period of time. In most cases, the crystal growth process took place over several hours and no significant settling took place before two hours. The exception was the aluminum oxide hydroxide or aluminum oxyhydroxide precipitate that formed within the reaction vessels before any cooling took place. This precipitation was driven by supersaturation caused by rapid corrosion of aluminum in alkaline solution at elevated temperatures.

Three precipitates formed due to chemical reactions of dissolved containment materials with each other or with the coolant pH buffer. When trisodium phosphate (TSP) was added to the dissolved solutions for CalSil and concrete in order to adjust the pH to 8, phosphate precipitate formed. In the combination precipitation tests using sodium tetraborate, no additional precipitates were formed due to chemical reaction with the sodium tetraborate. Also, a precipitate believed to be sodium calcium aluminum silicate formed from the combination of fiberglass and CalSil.

None of the thirteen precipitates described above settled rapidly; thus, in a post-accident environment, the precipitates would not be expected to settle before being transported to the sump screen.

The tests from which these precipitates formed are listed in Table 5.2-5.

Chemical Model

The results of the bench testing demonstrated that the predominant chemical precipitates are aluminum oxyhydroxide, an aluminum silicate such as sodium aluminum silicate, and calcium phosphate (for plants using trisodium phosphate for pH control). The first step of the chemical model predicts both the rate of dissolution and the solubility limits for the aluminum, calcium and silicon elements at selected times after a Loss of Coolant Accident (LOCA). For the second step, all of the material dissolved into solution is conservatively assumed to form precipitate due to the limited solubility of the key chemical precipitates. Both solution concentrations of the dissolved elements and the potential mass of the three main precipitate types are calculated as a function of time.

Particulate Generator

Testing of the proof-of-principle particulate generator demonstrated that representative particulates for the precipitates formed during the bench testing and predicted using the chemical model could be successfully generated for use in sump screen head loss testing. The chemical precipitates are intended to be treated as another class of inert debris for strainer testing purposes. The particulate generator qualification testing confirmed that the quality and temperature of the water in which the particulates are generated is not critical. However, a critical parameter determined was the limitation on the concentration of particulates within the mixing tank. If large quantities of particulates are required for screen testing, the particulates may need to be prepared in multiple batches or additional mixing tanks.

1.0 REPORT OVERVIEW

The purpose of this report is to provide sufficient information for utility engineers to perform a plant-specific evaluation of potential post-accident chemical effects in containment sump fluids to support their response to GSI-191.

Section 2 of this report presents the background of the chemical effects issue, specifically outlining the Integrated Chemical Effects Test (ICET) program, and also provides the objective of this program.

Section 3 describes the scope of containment materials considered within this program and makes an effort to categorize these materials by base composition.

Section 4 contains the original test plan, STD-MC-05-15, Revision 4, "Test Plan: Bench Testing of Chemical Effects Supporting the Evaluation of Replacement Containment Sump Screen Designs" revised to reflect the testing performed.

Section 5 documents the bench testing performed in support of this program. The selection based on actual plant conditions of the testing parameters such as temperature and pH is discussed along with the containment materials tested. The functional requirements for the testing equipment and the test procedures for the dissolution and precipitation bench testing are presented. Also, the results of the tests performed are given.

Section 6 presents the chemical model developed from the results of the bench testing described in Section 5. The model predicts the type and amount of dissolved material based on the material concentrations input and the resulting precipitates from both cooling of and chemical reactions within the sump solution. The predicted quantity and types of precipitates formed is intended for use in plant-specific sump screen testing.

Section 7 describes the particulate generator to be used to generate the precipitates formed due to chemical effects in the containment sump post-accident for screen testing. This section includes a description of the proof-of-principle particulate generator and the qualification testing performed with this apparatus.

Section 8 presents directives for plant-specific application of this report. The first section describes the intended method of implementation of the WOG bench testing results for screen vendor testing of chemical precipitates. The second section provides directions for use of the chemical model presented in Section 6 for utilities to perform their plant-specific evaluation.

Four appendices are provided to support this report. The first two contain the detailed results gathered from the dissolution and precipitation bench testing. The third contains the test data from the follow-on precipitate filterability tests. The fourth appendix presents the detailed evaluations performed in the chemical model Excel spreadsheet.

2.0 INTRODUCTION

2.1 BACKGROUND

Pressurized Water Reactor (PWR) containment buildings are designed to both contain radioactive materials releases and facilitate core cooling in the event of a Loss of Coolant Accident (LOCA). The cooling process requires water discharged from the break and containment spray to be collected in a sump for recirculation by the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS). Typically, a containment sump contains one or more screens in series that protect the components of the ECCS and CSS from debris that could be washed into the sump. Debris generated by the action of the discharged water and the latent containment debris inside containment may be transported to the containment sump when the ECCS and CSS are realigned from injecting water from the Refueling or Borated Water Storage Tank (RWST or BWST). There is a high level of concern that this debris may form a debris bed at the sump screen that would sufficiently impede the recirculating flow as to challenge long-term core cooling requirements.

The NRC identified its concern regarding maintaining adequate long-term core cooling in Generic Safety Issue (GSI) 191. Generic Letter (GL) 2004-02, issued in September 2004, identified actions that utilities must take to address the sump blockage issue. The NRC's position is that plants must be able to demonstrate that debris transported to the sump screen after a LOCA will not lead to unacceptable head loss for the recirculation pumps, will not impede flow through the ECCS and CSS, and will not adversely affect the long-term operation of either the ECCS or the CSS. Generic Letter 2004-02 also identifies that all mitigating actions by plants be implemented by the end of December 2007 if required to enable licensees to demonstrate acceptable ECCS and CSS performance.

A major concern in evaluating the effects of the debris transported to the sump screen after a LOCA is the chemical products which may form in a post-LOCA sump environment. Materials present in containment may dissolve or corrode when exposed to the reactor coolant and spray solutions. This behavior would result in oxide particulate corrosion products and the potential for the formation of precipitates due to changes in temperature and reactions with other dissolved materials. These chemical products may become another source of debris loading to be considered in sump screen performance and downstream effects.

2.2 INTEGRATED CHEMICAL EFFECTS TEST PROGRAM

The Integrated Chemical Effects Test (ICET) program (Reference 2.2-1) was sponsored jointly by the U.S. NRC and the nuclear utility industry, undertaken through the Memorandum of Understanding on Cooperative Nuclear Safety between NRC and the Electric Power Research Institute (EPRI), Addendum on Integral Chemical Effects Testing for PWR ECCS Recirculation. The ICET project simulated the chemical environment present inside a containment sump pool post-LOCA and monitored the chemical system for an extended period of time to identify the composition and physical characteristics of any chemical products formed during the test. The ICE test series was conducted by Los Alamos National Laboratory at the University of New Mexico with the assistance of the civil engineering department.

The objective of the ICET program was to determine, characterize, and quantify the chemical reaction products that may develop in a representative post-LOCA containment sump environment. The ICET program used five (5) test runs to study the long-term chemical reactions that may occur post-accident in a containment sump pool. The tests were representative of plants having one of three (3) buffer agents and two (2) types of insulation mixes. The buffer agents tested included all of the agents used in US PWRs. The insulation types were selected on the basis that these materials would be the primary debris materials added to the containment sump pool post-accident due to their extensive use inside containment. The test parameters (buffer agents and insulation mixes) are summarized in the following table.

Table 2.2-1: ICET Parameter Summary

Buffer Agent	Insulation Mix	
	100% Fiberglass	80% Calcium Silicate and 20% Fiberglass
Sodium Hydroxide	Test 1	Test 4
Trisodium Phosphate	Test 2	Test 3
Sodium Tetraborate	Test 5	

The ICE test parameters were defined prior to the availability of plant-specific debris generation and transport calculations performed in support of responding to GL 2004-02 (Reference 2.2-2). Thus a conservative approach was taken to estimate the amount of insulation debris that might be available to react post-accident inside a reactor containment building. Therefore, the amount of reactants (insulation debris) simulated in the ICE tests may be overly conservative relative to the amounts of reactants predicted to be available in operating PWRs.

Final data reports have been issued for four (4) of the five (5) ICE tests (References 2.2-3 - 2.2-6) as of this report. The data report for the fifth test has been reviewed and is currently undergoing comment resolution prior to publication. The NRC plans to publish an ICET program report as a nuclear regulatory guide (NUREG) document in the first quarter of 2006.

2.2.1 References

- 2.2-1 "Test Plan: Characterization of Chemical and Corrosion Effects Potentially Occurring Inside a PWR Containment Following a LOCA," Revision 13, July 20, 2005.
- 2.2-2 NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors, September 13, 2004.
- 2.2-3 LA-UR-05-0124, Integrated Chemical Effects Test Project: Test #1 Data Report, June 2005.
- 2.2-4 LA-UR-05-6146, Integrated Chemical Effects Test Project: Test #2 Data Report, September 2005.
- 2.2-5 LA-UR-05-6996, Integrated Chemical Effects Test Project: Test #3 Data Report, October 2005.
- 2.2-6 LA-UR-05-8735, Integrated Chemical Effects Test Project: Test #4 Data Report, November 2005.

2.3 PROGRAM OBJECTIVE

The objective of this program is to supplement and augment information obtained from the ICET program in order to provide information needed by plants to properly assess the potential for sump screen blockage by chemical precipitates. This information will be utilized by plants in submittals to the NRC to resolve safety issues identified in GSI-191 and further defined in GL 2004-2.

2.4 WOG CHEMICAL EFFECTS TEST PROGRAM

Specifically, more representative values of the following parameters were used:

1. Types of insulation: mineral wool, min-k, and other lesser-used insulations that were not evaluated in the ICET program were tested for post-accident chemical effects.
2. Amount of insulation: debris generation calculations, not available when the ICE test plan was generated, were used to guide the selection of appropriate quantities of debris to be used in the testing.
3. Temperature effects: the ICE tests evaluated long-term chemical effects by maintaining a constant temperature of 140°F. This test program evaluated chemical effects at sump water conditions representative of early in the transient (within 30 minutes of the postulated break). Using conservative licensing-basis assumptions, sump liquid temperatures are calculated to reach values of up to about 265°F during this 20-40 minute period.

Additional values taken from recent analytical work performed to support responses to GL 2004-02 will be used, when available and appropriate, to guide the selection of test parameters.

The tests performed in support of this program did not include an investigation of all possible chemical reactions of containment materials. The ICET program and the known properties of containment materials were used to select a number of tests that target the chemical reactions expected to generate the most precipitate. The selection of materials was based on the amount of material that may react and the reaction capability of the material. A technical basis for not including certain materials in the program (i.e., known reactions, minute quantities, etc.) follows in Section 3.2.

3.0 CONTAINMENT MATERIALS

In order to select the materials and their representative amounts for the bench testing, plant surveys were collected delineating the types and quantities of material present in containment. These materials include both hot-dipped and electroplated galvanized steel, untopcoated zinc coating, aluminum, copper, copper-nickel alloy, carbon steel, exposed concrete surface, fiberglass insulation, calcium silicate insulation, and other types of insulation. The minimum recirculation water volume was also obtained in order to determine the maximum ratio of material to sump volume for testing. Surveys were received and incorporated into the program for all of the sixty-nine (69) PWR plants.

3.1 COMPREHENSIVE LIST OF CONTAINMENT MATERIALS

Table 3.1-1 presents all the materials listed on the plant survey responses as being either exposed to the spray solution or submerged in the containment sump pool post-LOCA. The maximum plant ratios of material amount to minimum recirculation water volume were obtained from the plant surveys and are presented for each material. Also, the number of plants with each material and buffering agent combination as determined from the survey responses is included in the table.

Table 3.1-1: PWR Containment Materials and Associated Buffering Agents

Containment Materials		Number of Plants with Material	Maximum Material to Recirculation Water Volume Ratio	Number of Plants with Material – Buffering Agent Combination		
				Trisodium Phosphate	Sodium Hydroxide	Sodium Tetraborate
Metals	Aluminum	69	5.42 ft ² /ft ³	29	29	11
	Carbon Steel	55	10.78 ft ² /ft ³	25	23	7
	Copper	65	11.11 ft ² /ft ³	27	27	11
	Galvanized Steel	69	19.47 ft ² /ft ³	29	29	11
	Untopcoated Zinc Coating	62	27.98 ft ² /ft ³	27	24	11
Concrete	Concrete	62	4.79 ft ² /ft ³	28	27	7
Insulation	3M Interam	2	2.8E-4 ft ³ /ft ³	2	0	0
	3M-M20C	1	2.5E-4 ft ³ /ft ³	0	0	1
	Armaflex / Anti-sweat rubber / Foam rubber	8	2.6E-4 ft ³ /ft ³	4	4	0
	Asbestos	6	0.01 ft ³ /ft ³	0	6	0
	Benelex 401	1	3.8E-4 ft ³ /ft ³	0	1	0
	Calcium Silicate	28	0.18 ft ³ /ft ³	8	16	4
	Cerablanket	2	1.1E-4 ft ³ /ft ³	0	2	0
	CP-10	1	1.0E-4 ft ³ /ft ³	0	1	0
	Fiberglass Fiber	61	0.23 ft ³ /ft ³	27	28	6
	Foamglas	3	5.4E-3 ft ³ /ft ³	2	1	0
	Kaowool	6	0.02 ft ³ /ft ³	2	4	0
	Kaylo	1	3.9E-3 ft ³ /ft ³	0	1	0

Containment Materials		Number of Plants with Material	Maximum Material to Recirculation Water Volume Ratio	Number of Plants with Material – Buffering Agent Combination		
				Trisodium Phosphate	Sodium Hydroxide	Sodium Tetraborate
Insulation Continued	Leadwool	2	2.4E-4 ft ³ /ft ³	2	0	0
	Marinite	6	1.2E-3 ft ³ /ft ³	0	4	2
	Mat-Ceramic	1	2.9E-5 ft ³ /ft ³	0	1	0
	Microtherm	13	5.5E-4 ft ³ /ft ³	6	2	5
	Mineral Fiber	1	7.5E-3 ft ³ /ft ³	1	0	0
	Min-K	15	1.3E-3 ft ³ /ft ³	6	6	3
	Mineral Wool / MinWool	11	0.04 ft ³ /ft ³	4	7	0
	Mudd	2	8.6E-4 ft ³ /ft ³	0	0	2
	PAROC Mineral Wool	2	5.6E-4 ft ³ /ft ³	0	2	0
	Tempmat	7	5.1E-3 ft ³ /ft ³	0	7	0
	Thermal Wrap	7	0.03 ft ³ /ft ³	0	3	4
	Thermolag 330-1	5	9.4E-5 ft ³ /ft ³	4	1	0
	Transite	1	1.9E-3 ft ³ /ft ³	0	1	0
	Unibestos	1	1.4E-3 ft ³ /ft ³	0	1	0
	Vinylcel	1	Not provided	1	0	0

3.2 CLASSIFICATION OF CONTAINMENT MATERIALS

The base chemical composition of each containment material was determined from published information, including information from product data sheets, material safety data sheets, vendor web sites and text books. For natural products such as asbestos and vermiculite, nominal composition data were used. The data were tabulated in Table 3.2-1 and were used to establish general classifications of the materials. These classifications are discussed in this section and are summarized in Table 3.2-2.

Aluminum

This classification includes all aluminum alloys. Aluminum is primarily present as structural members, coatings, small components (e.g., valves) and thin foil coatings on insulation. Commercially pure aluminum (SA 1100) was used for bench-scale dissolution testing. This approach is considered to be conservative since aluminum alloys are typically more corrosion resistant than pure aluminum¹.

Aluminum Silicate

This classification includes both synthetic aluminum silicate insulation materials and natural aluminum silicates such as kaolin clay and vermiculite. The containment materials represented in this classification are 3M M-20C insulation^{2,3}, 3M I-Series insulation^{3,4}, Cerablanket⁵, Fiber Frax Durablanket⁶, Kaowool⁵, Mat-Ceramic insulation⁵, mineral fiber^{3,7}, and PAROC mineral wool⁸. Fiber Frax Durablanket was used in bench-scale dissolution testing to represent this material class.

Calcium Silicate

This classification includes low-density calcium silicate mat insulation, asbestos and asbestos-containing insulation, and the high density refractory materials (e.g., transite). The containment materials represented in this classification are asbestos, Cal-Sil insulation⁹, Kaylo¹⁰, marinite¹¹, Mudd¹², transite¹³, and Unibestos¹⁴. Low-density calcium silicate was used in bench-scale dissolution testing to represent this material class.

Asbestos is a broad classification of naturally-occurring minerals that are primarily mixed metal silicates¹⁵. Most forms of asbestos are typically resistant to dissolution under a broad pH range. To bound all asbestos materials, it was assumed that all asbestos is chrysotile (primarily magnesium silicate), and has the same dissolution behavior as calcium silicate. This conservative assumption is considered acceptable due to the low occurrence of asbestos.

Carbon Steel

This classification includes all uncoated/ungalvanized carbon and low alloy steels. These materials are typically present as structural members. Carbon steel SA 508 Class 2 was used in bench-scale dissolution testing to represent this material class. Although no steps were taken to intentionally pre-oxidize the specimens, a thin natural, low temperature oxide was present.

Concrete

Concrete is a complex mixture of cement, natural sand and gravel/rocks (all primarily silicon dioxide), and admixing agents (e.g., fly ash)¹⁶. Cement is prepared by heating a mixture of calcium oxide and silicate-containing materials to create tricalcium silicate and dicalcium silicate. Based on the base composition of concrete, the dissolution behavior of this material could reasonably be expected to be similar to that of calcium silicate. However, concrete was classified as a distinct material since it is ubiquitous in PWR containments. Ground concrete was used in bench-scale dissolution testing to represent this material class. The concrete sample was aged for greater than 28 days prior to use. Use of ground concrete is considered conservative due to its high surface area relative to that of structural concrete.

Copper

This classification includes all copper-containing alloys. As demonstrated in prior testing and based on published data¹, this material class is resistant to corrosion under expected post-accident conditions. Therefore, this material was not included in the current test program.

E-Glass

This classification includes all fiberglass insulation and cellular glass. E-glass is an amorphous material containing silicon dioxide, calcium oxide, aluminum oxide and boric oxide³. The material is typically resistant to dissolution in aqueous solutions over a broad range of temperature and pH, but some reaction does occur at high temperatures in alkaline solution. The containment materials represented in this classification are all fiberglass insulation (unspecified manufacturers), Foamglas¹⁷, NUKON¹⁹, Temp-Mat²¹ and Thermal Wrap²². Unspecified fiberglass and NUKON were used in dissolution testing to represent this material class.

Amorphous Silica

Similar to the E-glass category, the amorphous silica class contains materials made up of predominately amorphous silica with a small percentage of E-glass. The containment materials in this classification are Min-K¹⁸ and Microtherm²⁰. Min-K was used in the bench-scale dissolution testing to represent this material class and was found to behave differently enough from the E-glass class to require its own class.

Interam E-Class Insulation

Interam E-Class insulation is nominally composed of a blanket of fibrous hydrated alumina and aluminum silicate, with an aluminum alloy foil outer layer²³. No other materials were of similar composition. Therefore, this classification only includes the Interam E-Class material, and this material was included in bench-scale dissolution testing.

Mineral Wool

This classification includes mineral wools produced from steel slag and rock wools produced from naturally-occurring minerals such as basalt and dolomite²⁴. Mineral wools are typically

slightly less resistant to chemical attack than rock wools²⁴. Steel slag is nominally composed of calcium oxide, silicon dioxide, iron oxides, iron metal and minor amounts of other metal oxides and sulfur⁷. The containment materials represented in this classification are Min-Wool²⁵ and rock wool (manufacturers unspecified). Min-Wool was used in bench-scale dissolution testing to represent this material class.

Nickel

This classification includes all nickel-containing alloys. As demonstrated in prior testing, and based on published data¹, this material class is resistant to corrosion under expected post-accident conditions. Therefore, this material was not included in the current test program.

Organic Mastics

This classification includes all mastic coatings that contain inorganic materials in organic binders. The containment materials represented in this classification are CP-10 and Thermolag 330-1. The inorganic components of these compounds are encased in polymeric materials, vinyl acetate for CP-10, epoxides for Thermolag, and thus would not be exposed to sump fluids^{26,27}. On this basis, these materials were not represented in bench-scale testing.

Other Organic Materials

This classification includes rubber, foam rubber, phenolic resins, pressed wood products, and liquid hydrocarbons. The containment materials represented in this classification are: Armaflex²⁸, Benelex 401²⁹, Kool-Phen³⁰, and RCP motor oil. Consistent with the protocols established in the ICET program, organic materials were generally excluded from bench-scale dissolution testing. The basis for excluding such materials is that they were judged to be unlikely to breakdown to produce precipitate-forming species under the temperature and chemistry conditions tested.

Reactor Coolant Oxides

This material class includes the nickel ferrite and other oxides typically present in the corrosion product film on the inner surfaces of the reactor coolant system during normal operation. Under accident conditions, a small fraction of this film may spall off or be solubilized due to oxidation of the coolant. Based on measured releases during intentional coolant oxidation routinely conducted as part of normal plant shutdown³¹, the magnitude of this release is expected to introduce a negligible quantity of material into the sump under accident conditions. Therefore, this material class was not included in the current test program.

Zinc

This classification includes galvanized coating on carbon steel, including both hot-dipped and electrodeposited galvanization, and zinc coatings. Hot-dipped galvanized steel was used in bench-scale dissolution testing to represent this material class. Organic zinc coatings in which zinc is bound in an organic matrix, and therefore not exposed to the coolant, should be classified under "Other Organic Materials." Other organic zinc coatings should be treated as zinc metal.

Table 3.2-1: Base Composition of Containment Materials

Material	Composition	Notes
3M Interam E-5	70% hydrated alumina, 25% aluminum silicate, 3% metal foil (aluminum alloy), organic binders	
3M M-20-C	50% vermiculite (aluminum and magnesium silicate + other metal silicates), 13% aluminum silicate, foil/binders	
Aluminum	aluminum	
Armaflex	nitrile rubber + PVC	
Asbestos	magnesium silicate + other metal silicates	
Benelex 401	lignocellulose hardboard (pressed wood)	
Calcium Silicate Insulation	calcium silicate	
Cerablanket	100% aluminosilicate	
Concrete	>80% silicon dioxide, 13% cement	3
CP-10	20% silica (quartz), 12% hydrated alumina, 5% titanium dioxide + vinyl acetate	
Fiberfrax Durablanket	100% aluminosilicate	
Fiberglass Fiber	>95% E-glass + <5% binders	1
Foamglas	100% E-glass	1
Kaowool	80% aluminum silicate + 20% kaolin clay (hydrated aluminum silicate)	4
Kaylo	90% calcium silicate + 10% asbestos	5
KoolPhen	phenolic resin	
Marinite	70% calcium silicate + 22% calcium metasilicate + organic fiber + fiberglass	6
Mat-Ceramic	100% aluminosilicate	
Microtherm	90% (amorphous silica + silicon carbide) + 10% (E-glass + aluminum oxide)	1
Mineral Fiber	100% aluminosilicate	
Min-K	amorphous silica + E-glass (fiberglass)	1
MinWool	steel slag + 5% phenolic resin binder	2
Mudd	>50% calcium silicate, >10% cement, 10% (silicon dioxide + aluminum oxide) + other metal oxides/silicates	
Nukon Base Wool	>95% E-glass (fiberglass) + <5% binders	1
PAROC Mineral Wool	100% aluminosilicate	

Material	Composition	Notes
Tempmat	100% E-glass fiberglass	1
Thermal Wrap	>95% E-glass (fiberglass) + <5% binders	1
Thermolag 330-1	6% silicon dioxide (quartz), 3% E-glass (fiber glass) + epoxides	
Transite	70% calcium silicate + 22% calcium metasilicate + organic fiber + fiberglass	6
Unibestos	calcium silicate + asbestos (magnesium silicate)	

Notes:

1. E-glass is nominally composed of: 52-56% silicon dioxide, 16-25% calcium oxide 12-16% aluminum oxide, 5-10% boric oxide and minor amounts of sodium oxide, potassium oxide magnesium oxide iron (III) oxide, and titanium oxide.
2. Steel slag is nominally composed of: 40-52% calcium oxide, 10-19% silicon dioxide, 7-30% iron (II) oxide, 2 10% iron (III) oxide, 5% manganese oxide, 5% magnesium oxide, and minor amounts of aluminum oxide, phosphorous pentoxide, sulfur and iron.
3. Cement is predominantly dicalcium and tricalcium silicate, with minor amounts of calcium oxide, aluminum silicate, ferroaluminum silicate and other metal silicates.
4. This material may contain minor amounts of other inert additives such as titanium dioxide.
5. Newer material may contain other silicates in place of asbestos.
6. Transite is a higher density version of marinite.

Table 3.2-2: Containment Material Classification Summary

Material Class	Materials in Class	Representative Material
Aluminum	Aluminum alloys, aluminum coatings	Aluminum (pure)
Aluminum silicate	Cerablanket, FiberFrax Durablanket, Kaowool, Mat-Ceramic, Mineral Fiber, PAROC Mineral Wool	FiberFrax Durablanket
Calcium silicate	Asbestos, Cal-Sil insulation, Kaylo, Marinite, Mudd, Transite, Unibestos	Cal-Sil Insulation
Carbon Steel	All carbon and low alloy steels	SA 508 Cl 2
Concrete	Concrete	Ground Concrete
E-glass	Fiberglass insulation, NUKON, Temp-Mat, Foamglas, Thermal Wrap	NUKON, Unspecified Fiberglass
Amorphous Silica	Min-K, Microtherm	Min-K
Interam E Class	Interam E Class	Interam E-5
Mineral wool	Min-Wool, Rock Wool	Min-Wool
Zinc	Galvanized steel, zinc coatings	Galvanized Steel
Copper	All copper alloys	None
Nickel	All nickel alloys	None
Organic Mastics	CP-10, ThermoLag 330-1	None
Other Organics	Armaflex, Kool-Phen, Benelex 401, RCP motor oil	None
Reactor Coolant Oxides	nickel ferrite and other oxides	None

3.2.1 References

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4.0 TEST PLAN

4.1 INTRODUCTION

The test plan presented in this chapter was reviewed and commented upon by the nuclear industry through the Nuclear Energy Institute (NEI). An overview of the test plan was presented to the NRC at a public meeting on November 2, 2005 and comments were received both orally and in written form. The test plan was revised to incorporate industry and NRC suggestions and the final version was issued on November 22, 2005 (Reference 4.4-3).

4.1.1 Background

Pressurized Water Reactor (PWR) containment buildings are designed to both contain radioactive materials releases and facilitate core cooling in the event of a Loss of Coolant Accident (LOCA). The cooling process requires water discharged from the break and containment spray to be collected in a sump for recirculation by the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS). Typically, a containment sump contains one or more screens in series that protect the components of the ECCS and CSS from debris that could be washed into the sump. Debris generated by the action of the discharged water, and the latent containment debris inside containment, may be transported to the containment sump when the ECCS and CSS are realigned from injecting water from the Refueling or Borated Water Storage Tank (RWST or BWST). There is a high level of concern that this debris may form a debris bed at the sump screen that would sufficiently impede the recirculating flow as to challenge long-term core cooling requirements.

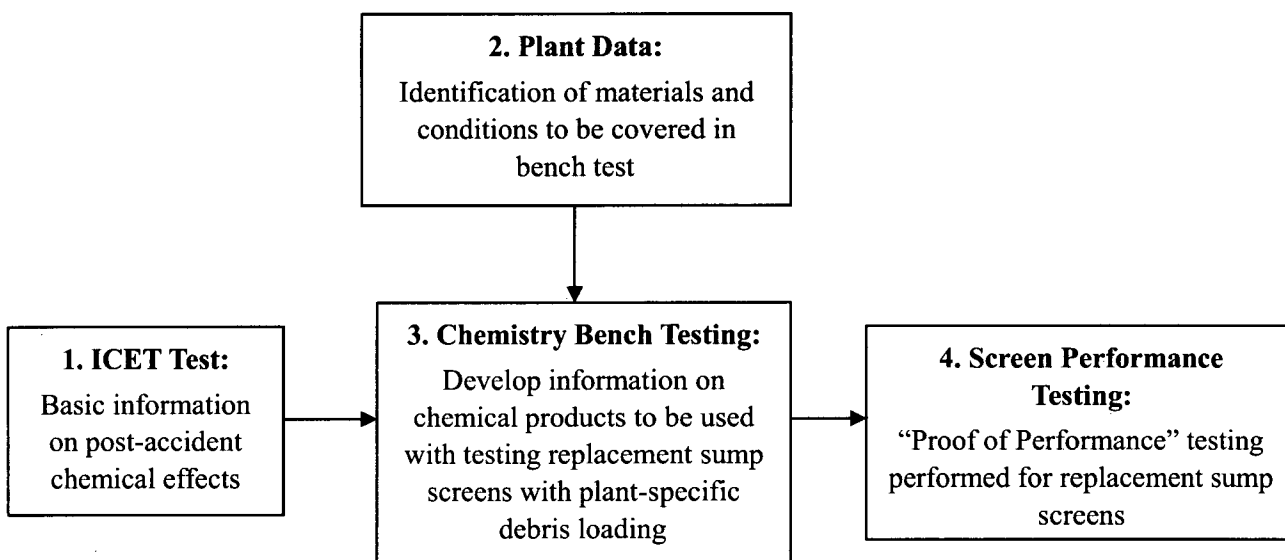
The NRC identified its concern regarding maintaining adequate long-term core cooling in Generic Safety Issue GSI-191. Generic Letter 2004-02, issued in September 2004, identified actions that utilities must take to address the sump blockage issue (Reference 4.5-2). The NRCs position is that plants must be able to demonstrate that debris transported to the sump screen after a LOCA will not lead to unacceptable head loss for the recirculation pumps, will not impede flow through the ECCS and CSS, and will not adversely affect the long-term operation of either the ECCS or the CSS. Generic Letter GL 2004-02 also identifies that all mitigating actions by plants, if required, to enable licensees to demonstrate acceptable ECCS and CSS performance, be implemented by the end of December 2007.

4.1.2 Program Overview

As discussed below, the Integrated Chemical Effects Test (ICET) program (Reference 4.5-1) used five (5) test runs to study the long-term chemical reactions that may occur post-accident in a containment sump pool that was representative of plants having one of three (3) buffer agents and two (2) types of insulation mixes; 100% fiberglass and an 80% / 20% mix of calcium silicate and fiberglass insulations. Thus, while useful and informative, the ICET data is limited. Furthermore, as the ICET parameters were defined prior to the availability of plant-specific debris generation and transport calculations, the amount of reactants simulated in the ICE tests may be overly conservative. An assessment of the corrosion products that would be generated

with more representative debris quantities is appropriate. Thus, the goal of this program is to supplement and augment information obtained from the ICET program. The information flow associated with this program is shown schematically in Figure 4.1-1, below.

Figure 4.1-1: Schematic for Information Flow for Chemistry Effects Bench Tests



Briefly summarizing the information flow, starting from the left-hand side of Figure 4.1-1;

1. The ICE tests provide basic information on long-term post-accident sump chemical effects. That information includes the conditions and materials used in the test and the data that was collected, as well as conditions and materials not included in the ICE test and is used both as input to set the bench test conditions, and to define the plant-specific information requested of plants.
2. Using plant-specific input, specific materials and amounts of materials are selected for the bench testing.
3. The bench testing is conducted for the purpose of characterizing the type and amount of chemical products that are produced. The chemical products themselves are characterized with respect to settling.
4. This chemical product information generated from the bench testing is used as an input to performance testing to be conducted by licensees and vendors of replacement sump screens.

The merit of this approach to testing for this issue has been demonstrated in bench testing performed by Westinghouse in late September 2005. Separate effects bench tests with two simulated post-accident chemistry conditions were performed. A draft review of the results from both tests suggests that bench testing for chemical effects will provide useful and usable data to support both understanding of post-accident chemical effects and the performance testing of replacement sump screens.

The characterization of the chemical products from bench testing is also intended to support and be used in the downstream effects evaluation of chemical products on the ECCS and CSS flow path, and equipment (pumps valves, etc.) in that flow path.

4.1.3 Purpose of Bench Tests

The purpose of this test plan is to develop information to supplement and augment the information obtained from the ICET program. In five (5) tests, the ICET program examined the long-term chemical reactions, and the associated chemical reaction products, that may occur in a simulated containment sump environment using two (2) types of thermal insulation materials and three (3) buffer agents. The insulation mixes and the buffering agents studied in the ICET program are given in the table below.

Table 4.1-1: Summary of ICE Test Matrix

Thermal Insulation	Buffer Agent		
	Sodium Hydroxide	Trisodium Phosphate	Sodium Tetraborate
100% Fiberglass	ICET Test 1	ICET Test 2	ICET Test 5
80% Calcium Silicate / 20% Fiberglass	ICET Test 4	ICET Test 3	

Knowing that the number of tests to be run as part of the ICET program was limited, criteria were established to guide the selection of test parameters.

1. The selection of the insulation types and buffer agents used in the ICE test were based on industry survey information and made with the objective of testing the most dominant types of thermal insulations and buffer agents that would react in the containment sump pool post-accident.
2. The selection of the amount of insulation to be used in the test was based on early data regarding the volume of debris that would be generated from a postulated high energy line break and selected to be representative of the fleet of PWR plants licensed to operate in the US.

Thus, the ICET results are not all-inclusive of all insulation types that might be in containment, and may excessively account for insulation debris in the containment sump.

4.2 SUPPLEMENTAL CHEMISTRY EFFECTS PROGRAM

Therefore, an additional chemistry effects test program is to be performed. The purpose of this additional program is to supplement and augment the data obtained from the ICET program. Specifically, more representative values of the following parameters will be used:

1. Types of insulation; micro-therm, min-k, and other lesser-used insulations will be evaluated for post-accident chemical effects.

2. Amount of insulation; debris generation calculations, not available when the ICE test plan was generated, will be used to guide the selection of appropriate quantities of debris to be used in the testing.
3. Temperature effects; the ICE test evaluated long-term chemical effects by maintaining a constant temperature of 140 °F. This test program will evaluate chemical effects at sump water conditions representative of early (within 30 minutes of the postulated break) in the transient. Using conservative licensing-basis assumptions, sump liquid temperatures are calculated to reach values of up to about 265 °F during this 20-40 minute period.

Additional values, taken from recent analytical work performed to support responses to Generic Letter GL 2004-02 will be used, when available and appropriate, to guide the selection of test parameters.

The tests described here do not include an investigation of all possible chemical reactions of containment materials. The ICET program and the known properties of containment materials have been used to select a number of tests that target the chemical reactions expected to generate the most precipitate. The selection of materials is based on the amount of material that may react, and the reaction capability of the material. A technical basis for not including certain materials in the program (i.e., known reactions, minute quantities, etc.) will be prepared for those materials, and will be documented in the project report.

4.2.1 Test Approach

The tests described here will be done at the “bench level” scale. This will allow testing to be completed in a time and cost effective manner.

First, using standard techniques, the dissolution rate for each of the containment materials of interest will be measured.

1. This will be done as a function of pH and temperature.
2. Interactions between dissolved matter from the various materials to form precipitates will then be measured as well as precipitate formation upon cooling.
3. This data will be used to construct a model that will take plant specific containment material mixes and conservatively predict amounts and character of precipitates that will form for a large break LOCA.

This information is essential for subsequent testing performed to demonstrate sump screen margin in performance tests. Functional requirements will be developed for equipment that can produce the type and quantity of precipitates needed for such tests.

Additional information, taken from recent analytical work performed to support responses to Generic Letter GL 2004-02 will be used, when available and where possible, to guide the selection of test parameters.

The tests described here do not include an investigation of all possible chemical reactions of containment materials. The ICET program and the known properties of containment materials have been used to select a number of tests that target the chemical reactions expected to generate the type and quantity of precipitates most likely to affect sump screen performance.

The approach used to develop the test plan was to produce reasonable but conservative estimates for precipitate formation. Dissolution rates will be measured for each containment material individually. These rates are expected to be higher than that obtained from containment material mixtures. This is because the dissolution of one material will have either no effect or an inhibiting effect on the dissolution of other materials. For instance:

1. The results of ICET Test 4 suggest that Cal-Sil inhibits the dissolution of aluminum. However, the region of influence for some LOCAs will not include Cal-Sil, even at a plant with a large volume of Cal-Sil.
2. Similarly, trisodium phosphate may inhibit the dissolution of Cal-Sil, but the trisodium phosphate in containment will take a finite period of time to dissolve. Thus, there may be some period during which dissolution of Cal-Sil is not influenced by the presence of trisodium phosphate.

The bench testing will be performed at temperatures up to a maximum value determined from industry surveys of containment pool temperatures that are expected after a large break LOCA before recirculation. This allows reactions during the first hours of a LOCA to be considered.

Consideration of the dissolution and precipitation reactions in separate bench-scale tests simplifies the interpretation of results and enables the use of the precipitation in chemical modeling. If integrated testing was performed with complex mixtures of materials, dissolution and precipitation occur simultaneously, making weight loss and gain information minimally useful. Integrated tests, while realistic, produce complex mixtures of products that are difficult to analyze.

4.2.2 Dissolution Testing

The dissolution of each of the following materials will be measured at temperatures determined from industry surveys with a range of pH values that are experienced in the post LOCA environment.

1. The maximum pH will be 12.0 and will be generated with sodium hydroxide (NaOH). This value is slightly higher than the maximum pH expected for a plant using NaOH pH buffering.
2. An intermediate pH of 8 will be tested. This is a typical containment pool pH after complete addition of the pH buffering agent in plants using trisodium phosphate or sodium tetraborate.
3. The minimum pH will be approximately 4.1 and will be generated with 4400 ppm boric acid. This is the lowest pH expected for all plants before buffering agent addition is

completed. Although the majority of plants are bounded by a boric acid concentration of 2800 ppm, the difference in pH is small at 4.4 vs. 4.1 with 4400 ppm boric acid, and boron (as borate) is not a critical complex in key precipitation reactions. Note, the levels of acidic radiolysis products such as hydrochloric acid are not expected to be significant early in a postulated event prior to completion of buffering agent addition. After dissolution of the buffering agent, the long term generation of HCl will have little effect on pH. The large excess of the buffering agent will set the pH.

The pH values listed are starting values. The pH will vary as the containment materials dissolve.

Materials to be tested include, as a minimum:

- Aluminum sheet
- Cal-Sil insulation
- NuKon-fiberglass
- Previously untested fiberglass (Temp Mat)
- Powdered concrete
- Mineral Wool (e.g. K-Wool)
- Microporous Insulation (e.g. Kool-phen-K)
- Fire Retardant Material (e.g. FiberFrax)

Note, the material list was amended based on receipt of additional industry input. Prior to use, specimens were pretreated as required to simulate prototypical material conditions. The pretreatment methods used will be consistent with industry standards and past testing, as documented in the project report.

The total amount of material dissolved after a minimum of two and a maximum of four time periods will be measured. It is anticipated that these time periods will have the following range:

1. The short time was 30 minutes. This is generally representative of the time from the initiation of the break to initiation of realigning of the ECCS to the recirculate from ion mode from the containment sump with all trains of the ECCS operating.
2. Additional samples were taken at sixty and ninety minutes. Sixty minutes is generally representative of the time from the initiation of the break to before initiation of realigning the containment sump to recirculate from the containment sump with only one train of ECCS operating.

Trisodium Phosphate Dissolution Rate

Information was collected from literature on the dissolution rate anticipated for trisodium phosphate after a LOCA. Additional bench scale testing was not determined to be necessary.

Corrosion Products from the RCS

Nickel and iron dissolution from the RCS will not be included in this testing. Normal PWR shutdown chemistry evolutions have shown the iron will be released at insignificantly low levels. Although nickel concentrations as high as 12 ppm may be expected, based on consideration of the counter ions present in the sump fluids and applicable chemistry conditions, it is not considered likely that any insoluble nickel compounds would be generated. This includes consideration of such possible species as phosphates, silicates, borates, and hydroxides/oxyhydroxides.. Based on experience with plant shutdown chemistry, it is considered likely that no more than a small quantity (<5 kg) of oxide (i.e., magnetite, nickel ferrite, etc.) would be released from the internal surfaces of the Reactor Coolant System during a LOCA. Any such material released would be in the form of a dense, crystalline deposit that would not be readily transported, and would not be expected to affect sump screen performance.

Table 4.2-1: Dissolution Test Matrix

Run	Test Conditions			Measurement	
	Material	Solution	T (°F)	Intermediate	Final
1	1. Aluminum sheet	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
2		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
3		pH 8 NaOH	265	ICP	Mass, ICP
4		pH 8 NaOH	190	ICP	Mass, ICP
5		pH 12 NaOH	265	ICP	Mass, ICP
6		pH 12 NaOH	190	ICP	Mass, ICP
7	2. Cal-Sil Insulation	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
8		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
9		pH 8 NaOH	265	ICP	Mass, ICP
10		pH 8 NaOH	190	ICP	Mass, ICP
11		pH 12 NaOH	265	ICP	Mass, ICP
12		pH 12 NaOH	190	ICP	Mass, ICP
13	3. NUKON Fiberglass	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
14		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
15		pH 8 NaOH	265	ICP	Mass, ICP
16		pH 8 NaOH	190	ICP	Mass, ICP
17		pH 12 NaOH	265	ICP	Mass, ICP
18		pH 12 NaOH	190	ICP	Mass, ICP
19	4. Other Fiberglass	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
20		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
21		pH 8 NaOH	265	ICP	Mass, ICP
22		pH 8 NaOH	190	ICP	Mass, ICP
23		pH 12 NaOH	265	ICP	Mass, ICP
24		pH 12 NaOH	190	ICP	Mass, ICP
25	5. Powdered Concrete	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
26		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
27		pH 8 NaOH	265	ICP	Mass, ICP
28		pH 8 NaOH	190	ICP	Mass, ICP
29		pH 12 NaOH	265	ICP	Mass, ICP
30		pH 12 NaOH	190	ICP	Mass, ICP
31	6. Mineral Wool	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
32		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
33		pH 8 NaOH	265	ICP	Mass, ICP
34		pH 8 NaOH	190	ICP	Mass, ICP
35		pH 12 NaOH	265	ICP	Mass, ICP
36		pH 12 NaOH	190	ICP	Mass, ICP
37	7. Microporous Insulation	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
38		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
39		pH 8 NaOH	265	ICP	Mass, ICP
40		pH 8 NaOH	190	ICP	Mass, ICP
41		pH 12 NaOH	265	ICP	Mass, ICP

42		pH 12 NaOH	190	ICP	Mass, ICP
43	8. Fiber Fax	4400 ppm B (as H ₃ BO ₃)	265	ICP	Mass, ICP
44		4400 ppm B (as H ₃ BO ₃)	190	ICP	Mass, ICP
45		pH 8 NaOH	265	ICP	Mass, ICP
46		pH 1 8 NaOH	190	ICP	Mass, ICP
47		pH 12 NaOH	265	ICP	Mass, ICP
48		pH 12 NaOH	190	ICP	Mass, ICP

ICP = analysis of dissolved elements by ICP

Mass = Final material mass

4.2.3 Precipitation Testing

The dissolved material from the Materials Dissolution Testing produced at maximum temperatures determined from industry surveys were cooled to 80°F to test for chemical precipitate formation. The value of 80°F is typical of long-term equilibrium pool temperatures, and can be reliably controlled in a laboratory environment.

The pH of the boric acid solutions were adjusted to pH = 8 in separate tests using sodium tetraborate and trisodium phosphate.

The following characteristics of the precipitate were measured using standard techniques:

- Precipitate mass
- Precipitate settling rate
- Settled precipitate volume
- Precipitate filterability

The potential for interaction between the different containment materials to produce precipitation beyond that produced from a single material were investigated with screening tests that measure the mass of precipitates only. Up to 10 combinations of material dissolution products were made before cooling and pH adjustment. The selection of the combinations were made on the basis of the most likely reactions. The results of the dissolution tests, combined with literature data, guided the selection of solutions to combine.

The precipitation test matrix is shown in the following table. Note: Solution numbers in the Solution A and Solution B columns refer to dissolution test numbers.

Table 4.2-2: Precipitation Test Matrix

PPT Run	Solution A	Solution B	Note
1	1	-	Precipitation from cooling
2	3	-	Precipitation from cooling
3	5	-	Precipitation from cooling
4	7	-	Precipitation from cooling
5	9	-	Precipitation from cooling
6	11	-	Precipitation from cooling
7	13	-	Precipitation from cooling
8	15	-	Precipitation from cooling
9	17	-	Precipitation from cooling
10	19	-	Precipitation from cooling
11	21	-	Precipitation from cooling
12	23	-	Precipitation from cooling
13	25	-	Precipitation from cooling
14	27	-	Precipitation from cooling
15	29	-	Precipitation from cooling
16	31	-	Precipitation from cooling
17	33	-	Precipitation from cooling
18	35	-	Precipitation from cooling
19	37	-	Precipitation from cooling
20	39	-	Precipitation from cooling
21	41	-	Precipitation from cooling
22	43	-	Precipitation from cooling
23	45	-	Precipitation from cooling
24	47	-	Precipitation from cooling
25	1	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
26	7	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
27	13	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
28	19	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
29	25	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
30	31	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
31	37	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
32	43	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
33	1	Borax pH 8	Precipitation due to pH Increase
34	7	Borax pH 8	Precipitation due to pH Increase
35	13	Borax pH 8	Precipitation due to pH Increase
36	19	Borax pH 8	Precipitation due to pH Increase
37	25	Borax pH 8	Precipitation due to pH Increase
38	31	Borax pH 8	Precipitation due to pH Increase
39	37	Borax pH 8	Precipitation due to pH Increase
40	43	Borax pH 8	Precipitation due to pH Increase
41-50	X	Y	Combinations will be selected on basis of dissolution tests

4.3 TEST OPERATIONS

4.3.1 Test Performer

The organization responsible for performing the bench tests described in this document is the Westinghouse Science and Technology Center (STC). Additional support will be obtained from other qualified facilities, as needed, and will perform under the direction of STC, to support and maintain the schedule identified below.

4.3.2 Procedures

Existing Westinghouse procedures and industry standard practices were used to prepare test specimens, perform testing, and collect the data identified in this document. Actions that are different from Westinghouse or industry standard practices were documented.

4.3.3 Equipment and Instrumentation

The following is a general description of equipment and instrumentation that were used in this test program.

1. A collection of heated reaction vessels, each having a volume of less than 1 gallon, were used for the dissolution testing.
2. Settling experiments were conducted in centrifuge tubes.
3. The filtration was performed with a commercial glass fiber filter. Scanning Electron Microscopy (SEM) techniques were used to examine the collection of filtrate, if determined to be appropriate. This will allow identification of the filtrate material as well as the mode of filtrate collection.

4.3.4 Documentation

Log books were maintained to record the activities associated with the performance of each test.

4.3.5 Photographs

Digital photographs were taken as follows:

Materials Dissolution Testing

1. Test samples, before being placed in solution

Precipitation Generation Testing

1. Precipitate settling rate; an attempt will be made to "mark" and "time phase" the photos to illustrate settling

-
2. The amount of settled precipitate; to illustrate the volume of precipitate

4.4 REFERENCES

- 4.4-1 "Test Plan: Characterization of Chemical and Corrosion Effects Potentially Occurring Inside a PWR Containment Following a LOCA," Revision 13, July 20, 2005.
- 4.4-2 Generic Letter GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized Water Reactors," September 13, 2005.
- 4.4-3 STD-MC-05-15, "Test Plan: Measurement of Chemical Effects Design Margin in Containment Sump Screens," Revision 4, November 22, 2005.

5.0 BENCH TESTING

The bench testing experiments explored the dissolution characteristics of containment materials and the characteristics of precipitates that were generated from dissolved containment materials. The experimental design for the dissolution tests and precipitation tests has been described in Section 4.0. The implementation of the test plan and the results that were obtained are described below.

5.1 PARAMETER SELECTION

The test plan stated that the final selection of operating temperatures, pH values, sampling times and materials would be made on the basis of the industry survey considering input from the NRC. These parameters were set as described below.

5.1.1 Dissolution Testing Temperature and pH

The industry survey data was reviewed and it was concluded that the pH levels of 4.1, 8.0 and 12.0 in the test plan adequately spanned the pH range expected in the sump after a LOCA. Likewise, the test plan maximum temperature of 265°F +/- 5°F was determined to be adequate in that it bounded all but one of the maximum temperature values in the industry survey. Because the one outlier was only 10°F higher than the maximum temperature range and lasts for just the first 40 seconds after the Reactor Coolant System (RCS) break, this brief spike in temperature is not expected to have a significant impact on the overall dissolution behavior considered over 90 minutes.

Sampling times for the dissolution test were set at 30 minutes, 60 minutes, and 90 minutes. These rather short dissolution times were selected for a number of reasons. The most important was that pH vs. time plots provided with the surveys indicated that the most extreme pH values were typically maintained for only a few minutes, so long term testing at the extreme values would not represent the expected containment conditions. Short term dissolution rates obtained with the 30, 60, and 90 minute sampling would be expected to bound long term corrosion rates in most cases since most corrosion/dissolution reactions slow with time. This would not be the case for materials with an induction period for dissolution, but the existence of an induction period could be identified by increasing dissolution during the initial 90 minutes. The testing time could then been extended for such a material. Finally, some of the existing dissolution data for CalSil suggested that dissolution rates were quite high, and short sampling times would be required to measure dissolution rates before saturation occurred.¹

5.1.2 Containment Materials

The materials investigated in the dissolution tests were selected so that at least one member of each of the containment material categories was included. See Section 3.2 for the classification of containment materials by chemical composition. Initially, the list included:

- Aluminum sheet
- Concrete (ground)

- CalSil
- Nukon Fiberglass
- High Density Fiberglass
- Mineral Wool
- Min-K
- FiberFrax Durablanket
- Interam

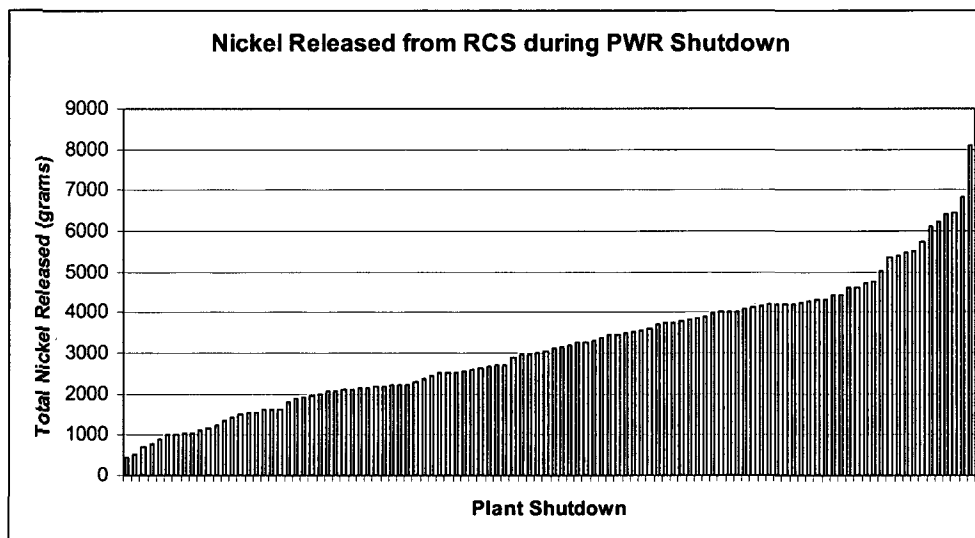
The NRC recommended the inclusion of galvanized steel and uncoated carbon steel in a review of the test plan during a program review at the Westinghouse Science and Technology Center on December 6, 2005 so these materials were also added to the dissolution test matrix.

- Galvanized steel
- Uncoated carbon steel

Copper alloy surfaces in containment can be significant but copper was not tested because the corrosion resistance of copper is similar to that of carbon steel or galvanized steel¹ and only very low solution copper concentrations were observed in the ICE tests. Previous testing by Oak Ridge National Laboratory has also concluded that “the corrosion rate of copper and the copper alloys is low enough in the alkaline borate solution to be of no practical concern.”²

Some dissolved material and suspended solids would be released from the reactor coolant system (RCS) during a LOCA. One would expect the levels to be similar to that experienced during a normal PWR shutdown. Dissolved nickel is the main component released from the RCS.¹ Nickel was not included in the materials investigated in the bench testing because the total quantity of nickel expected was small compared to other materials as shown in Figure 5.1-1.

Figure 5.1-1: Nickel Releases during Shutdowns for Three and Four Loop PWRs



A color macrograph of each of the tested materials is given in Figure 5.1-2. The approximate proportions of the materials used are shown except for carbon steel, where two and one-half coupons were tested. A more detailed description of materials is given in the remainder of the section.

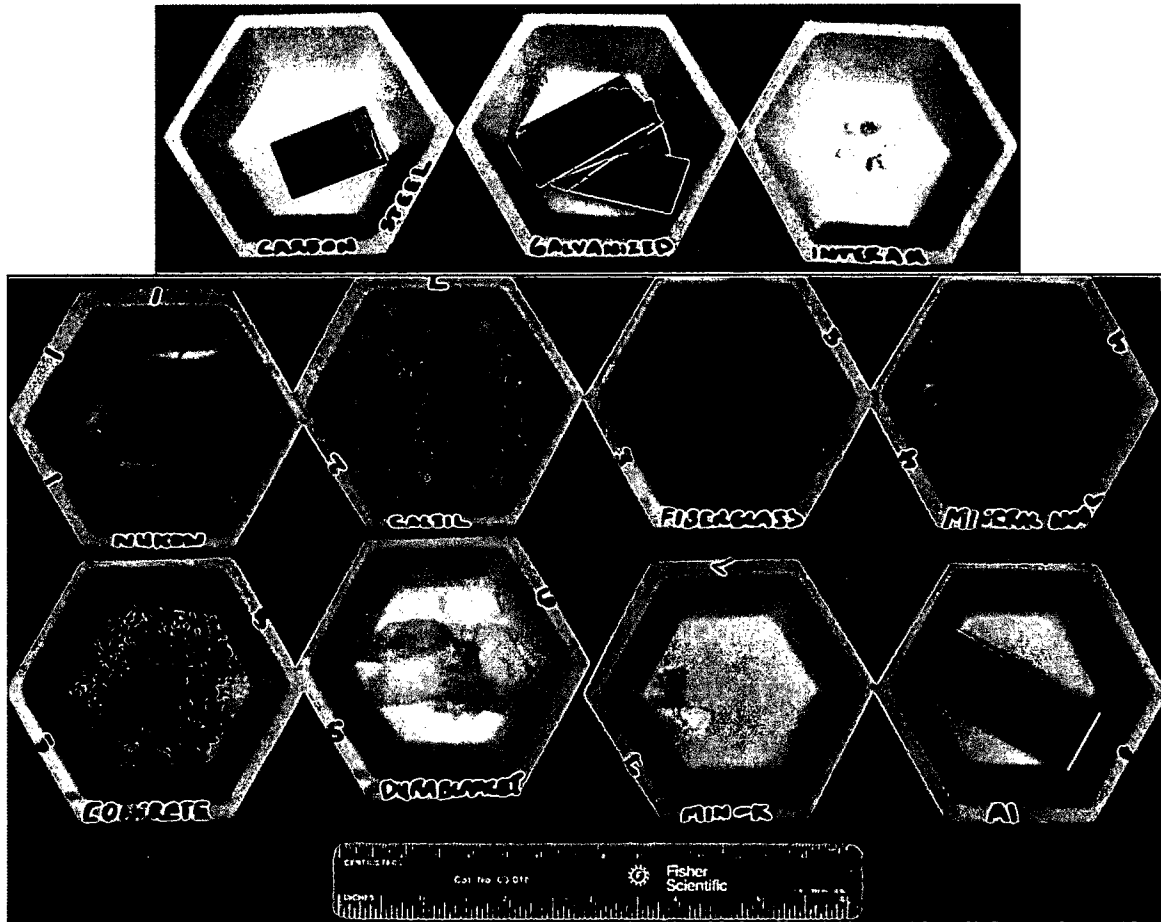


Figure 5.1-2: Light Macrophotos Starting Materials

5.1.2.1 Containment Material Details

Although carbon was detected in a number of the SEM samples, the majority of the carbon is most likely an artifact of the sample preparation. For insulation materials in which carbon may be present as an organic binder, the presence of carbon could reduce the measured dissolution rates, but experimentally, no effect was observed.

Aluminum Sheet

Aluminum Alloy 1100 (Commercially Pure) sheet 0.032 inches thick was supplied by McMaster Carr (Part Number 88685K11). The sheeting was cut with a shear into coupons that were 20 mm wide and either 31, 42 or 61mm long. The coupons were cleaned in water and ethanol but were not polished. The coupons were reflective, suggesting that the native oxide was relatively thin.

An SEM/EDS analysis was performed on the coupon surface. The SEM image is shown in Figure 5.1-3. Only the elements aluminum and iron were detected on the surface. Concentrations are given in Table 5.1-2.

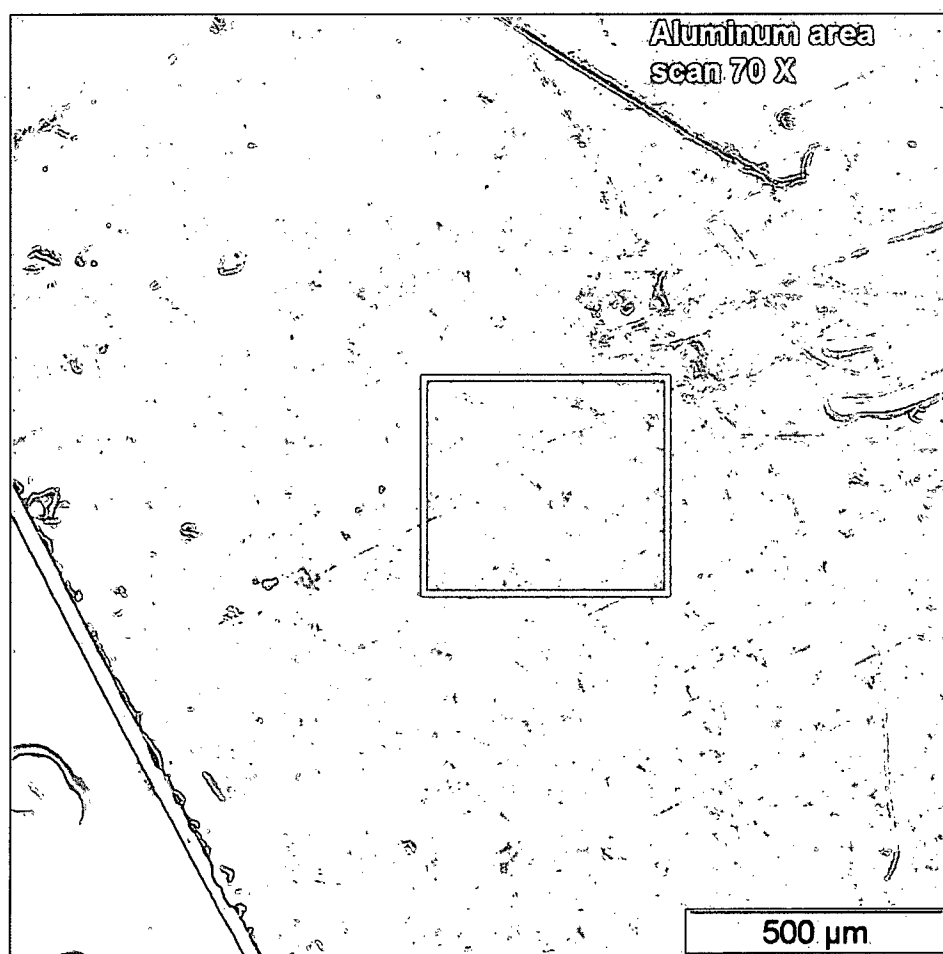


Figure 5.1-3: SEM Image of an Aluminum Coupon Surface

Concrete

Concrete was supplied by Performance Contracting, Inc. (PCI). The concrete had been crushed by PCI, and a large range of particle sizes were present. The largest were near 10 mm in diameter, while the smallest were only a few microns in diameter. The surface area of concrete exposed to solution will control the dissolution rate, so the surface areas of several concrete samples were measured by the BET method. The results are shown in Table 5.1-1.

Table 5.1-1: Concrete Specific Surface Area by BET

Sample Number	Specific Surface Area (m ² /g)
1	9.78
2	8.49
3	9.84
4	9.39
5	9.58
6	8.34
Average	9.24

The elemental composition determined by SEM/EDS is given in Table 5.1-2. Calcium, silicon, and oxygen were the primary components of the concrete. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of two concrete particles is shown in Figure 5.1-4.

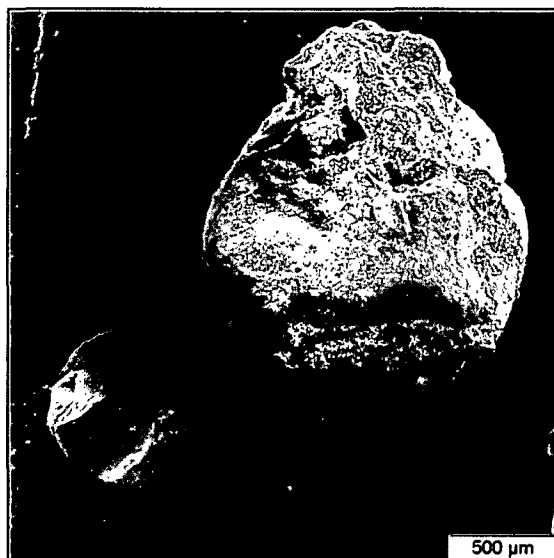


Figure 5.1-4: SEM Image of Two Concrete Particles

CalSil

CalSil was supplied by PCI, Inc. The CalSil had been crushed into a powdered form which is standard for GSI-191 testing.

The elemental composition determined by SEM/EDS is given in Table 5.1-2. Calcium, silicon, and oxygen were the primary components of the concrete. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging. The composition was quite similar to that of concrete.

An SEM image of CalSil particles and fibers is shown in Figure 5.1-5. The clumps of calcium silicate particles were loosely bound together with organic fibers.

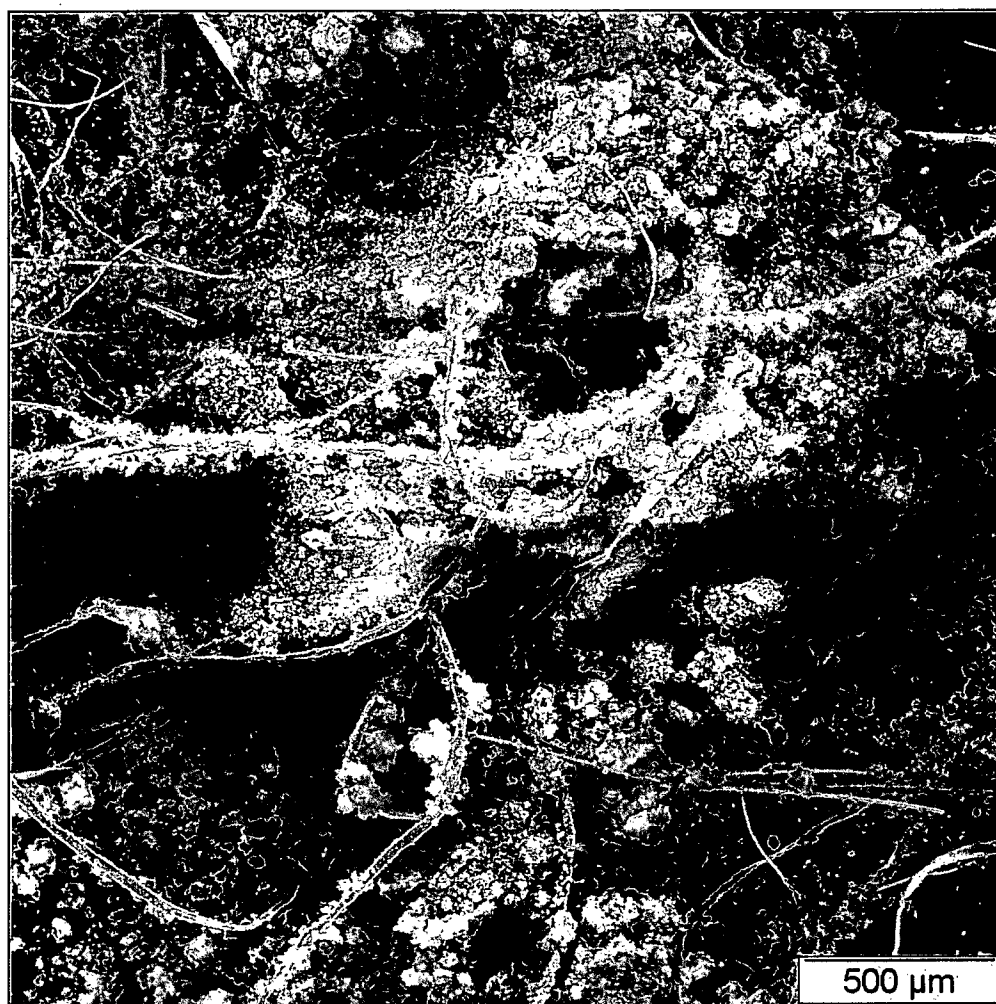


Figure 5.1-5: SEM Image of CalSil Fibers and Particles

Nukon Fiberglass

Nukon fiberglass was supplied by PCI, Inc. in a baked and shredded form.

The elemental composition of the Nukon as determined by SEM/EDS is given in Table 5.1-2. An area scan of a mass of fibers revealed that sodium, calcium, silicon, aluminum and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of Nukon fiberglass fibers is shown in Figure 5.1-6.

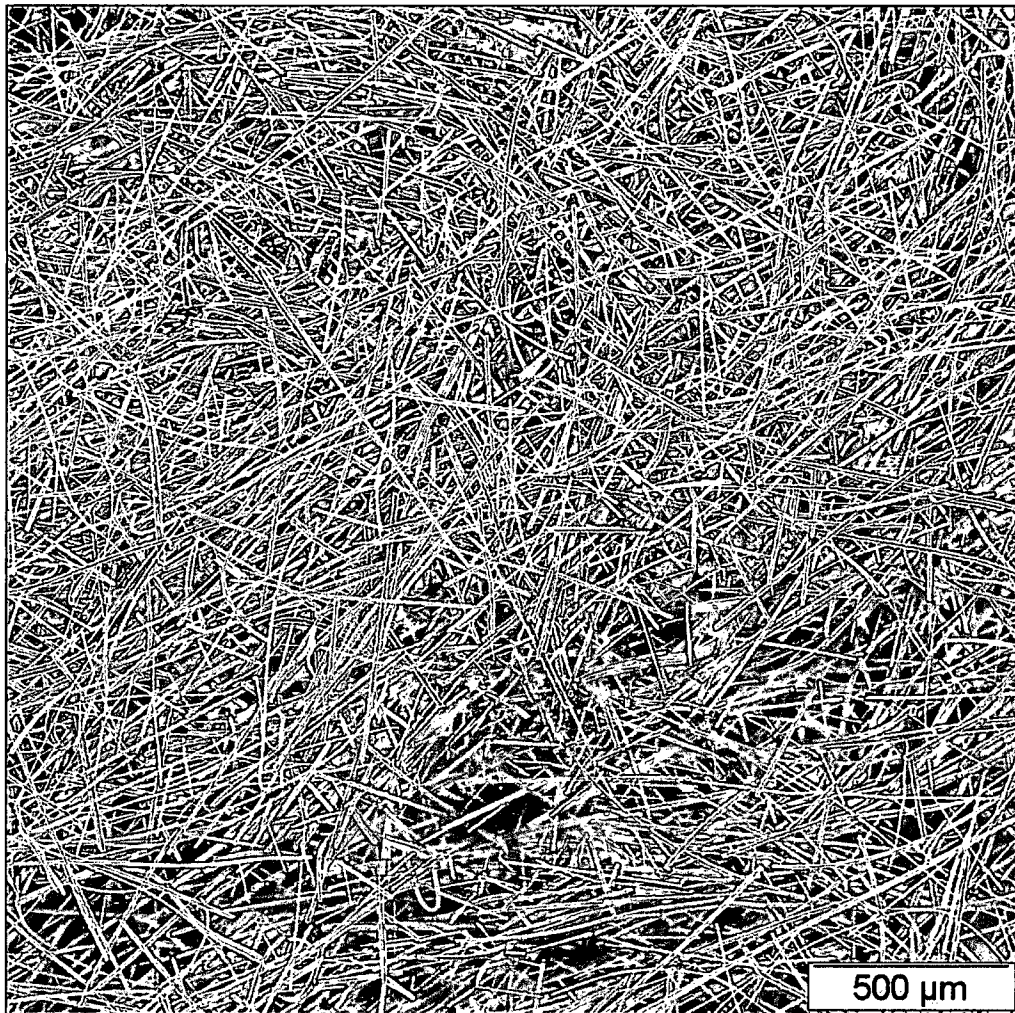


Figure 5.1-6: SEM Image of Nukon Fibers

High Density Fiberglass

The high density fiberglass was supplied in unbaked, shredded form by PCI. Since the high density fiberglass was unbaked, the organic binders present during testing could produce a non-conservative lower dissolution rate. However, this behavior was not observed as evidenced by the larger mass release in Table 5.2-2 for the high density fiberglass than that for the baked Nukon fiberglass.

The elemental composition of the high density fiberglass was determined by SEM/EDS and is given in Table 5.1-2. An area scan of a mass of fibers revealed that sodium, calcium, silicon, aluminum and oxygen were the primary components. Sulfur was a minor component not found in the Nukon sample. Carbon was detected at higher levels than in the Nukon fiberglass sample. The source of the additional carbon was likely the organic binder. The ratios of the main elemental components were similar between Nukon fiberglass and high density fiberglass. This is evident in Table 5.1-3, where oxygen and carbon have been removed from the analyses and the remaining elemental concentrations were renormalized.

An SEM image of high density fiberglass fibers is shown in Figure 5.1-7. Binding material can be seen connecting the fibers.

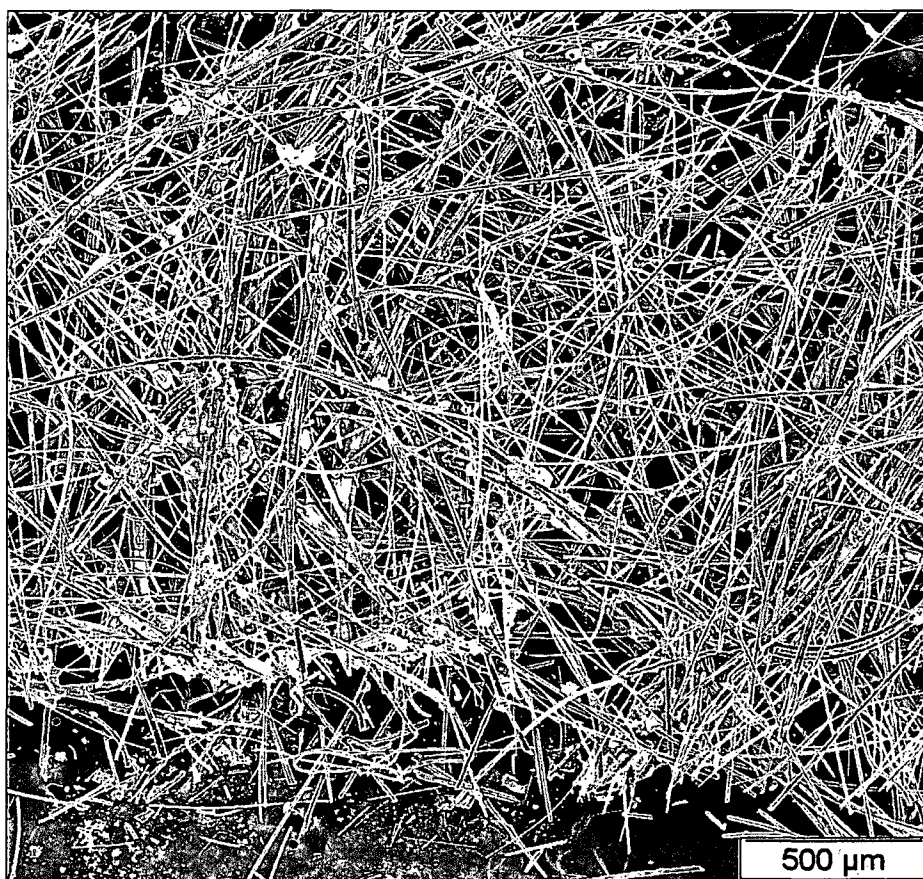


Figure 5.1-7: SEM Image of High Density Fiberglass Fibers

Mineral Wool

Mineral wool was supplied in shredded form by PCI, Inc. The mineral wool was not baked. Although this material was not baked, there was no clear evidence of organic binders.

The elemental composition of the mineral wool was determined by SEM/EDS and is given in Table 5.1-2. An area scan of a mass of fibers revealed that magnesium, calcium, silicon, aluminum, iron and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of the mineral wool sample is shown in Figure 5.1-8. The fibers and glassy droplets shown in the figure all had about the same chemical composition.

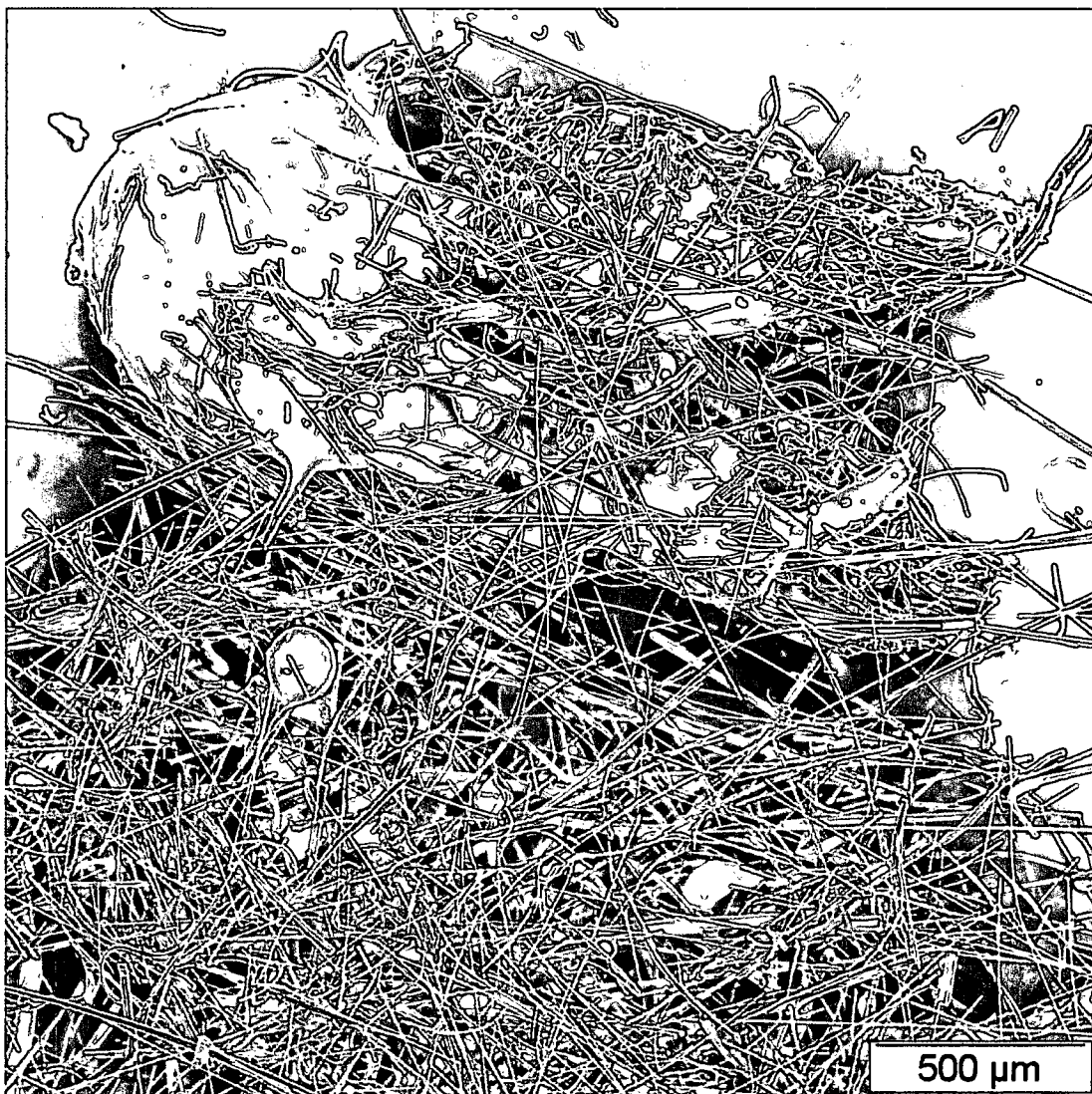


Figure 5.1-8: SEM Image of Mineral Wool

MIN-K

MIN-K was supplied in shredded form by PCI, Inc. The MIN-K was not baked. The presence or absence of binding materials was not clear, but as discussed for the high density fiberglass, the presence of organic binders may not exert a strong influence on dissolution behavior.

The elemental composition of the MIN-K was determined by SEM/EDS and is given in Table 5.1-2. It should be noted that the MIN-K was not homogeneous. E-Glass fibers were found to be located both in piles and in a woven fabric. Silica and titania particles clung to the fibers, and were present in separate clumps. An area scan in a region that contained both fibers and particles revealed that silicon, oxygen, titanium, and calcium were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging. Boron was a likely component of the fibers but it could not be quantified with the EDS system that was used.

An SEM image of the MIN-K sample is shown in Figure 5.1-9.

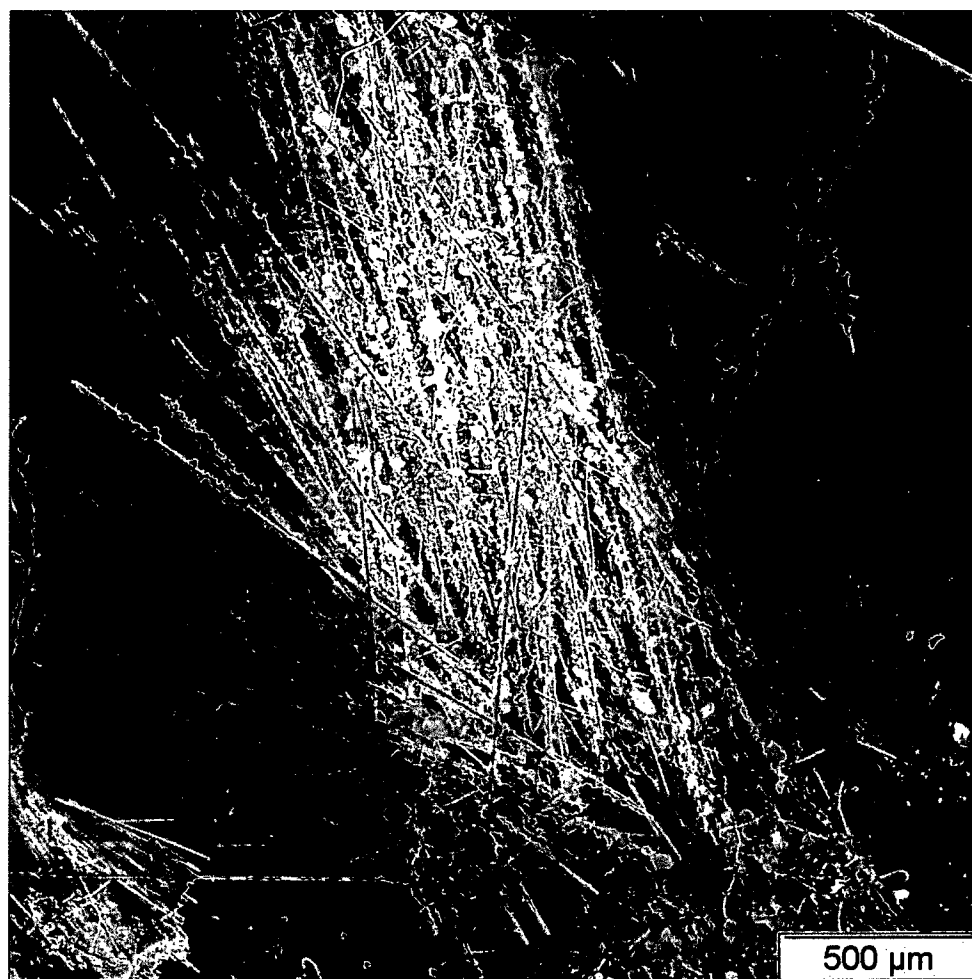


Figure 5.1-9: SEM Image of Fibers and Attached Particles in the MIN-K Sample

FiberFrax DuraBlanket

The FiberFrax DuraBlanket was supplied in shredded form by PCI, Inc. The FiberFrax was not baked and did not appear to contain any binders.

The elemental composition of the Fiber Frax was determined by SEM/EDS and is given in Table 5.1-2. The composition was uniform from location to location. The elements silicon, aluminum and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of the FiberFrax Durablank sample is shown in Figure 5.1-10.

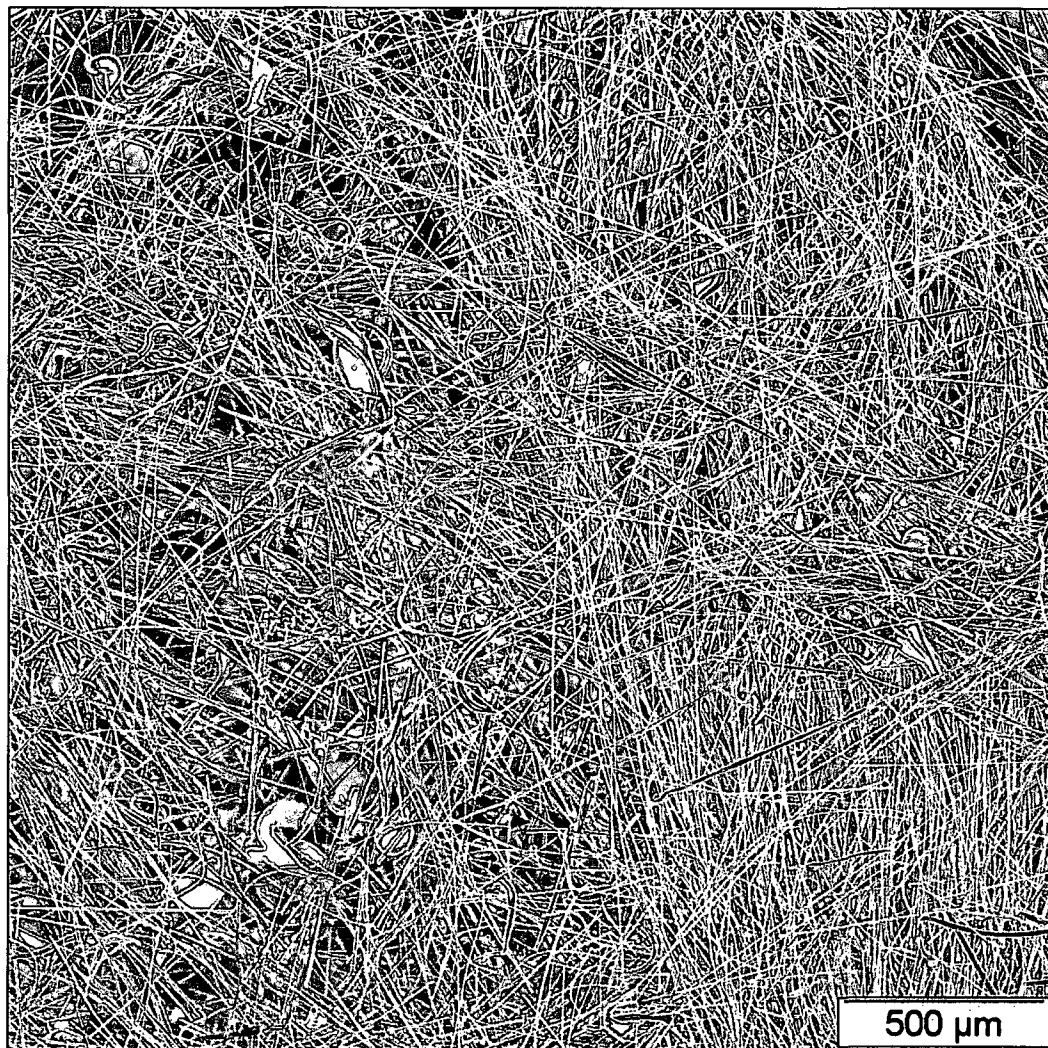


Figure 5.1-10: SEM Image of FiberFrax Durablanket

Interam

The Interam was supplied by Southern Nuclear. The Interam was supplied as a single foil-backed sheet of insulation. The sheet was sampled by slicing a thin strip of material from the edge of the sheet. The samples included the aluminum backing.

The elemental composition of the Interam filler was determined by SEM/EDS and is given in Table 5.1-2. The elements silicon, aluminum, calcium and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of a portion of the Interam sample is shown in Figure 5.1-11.

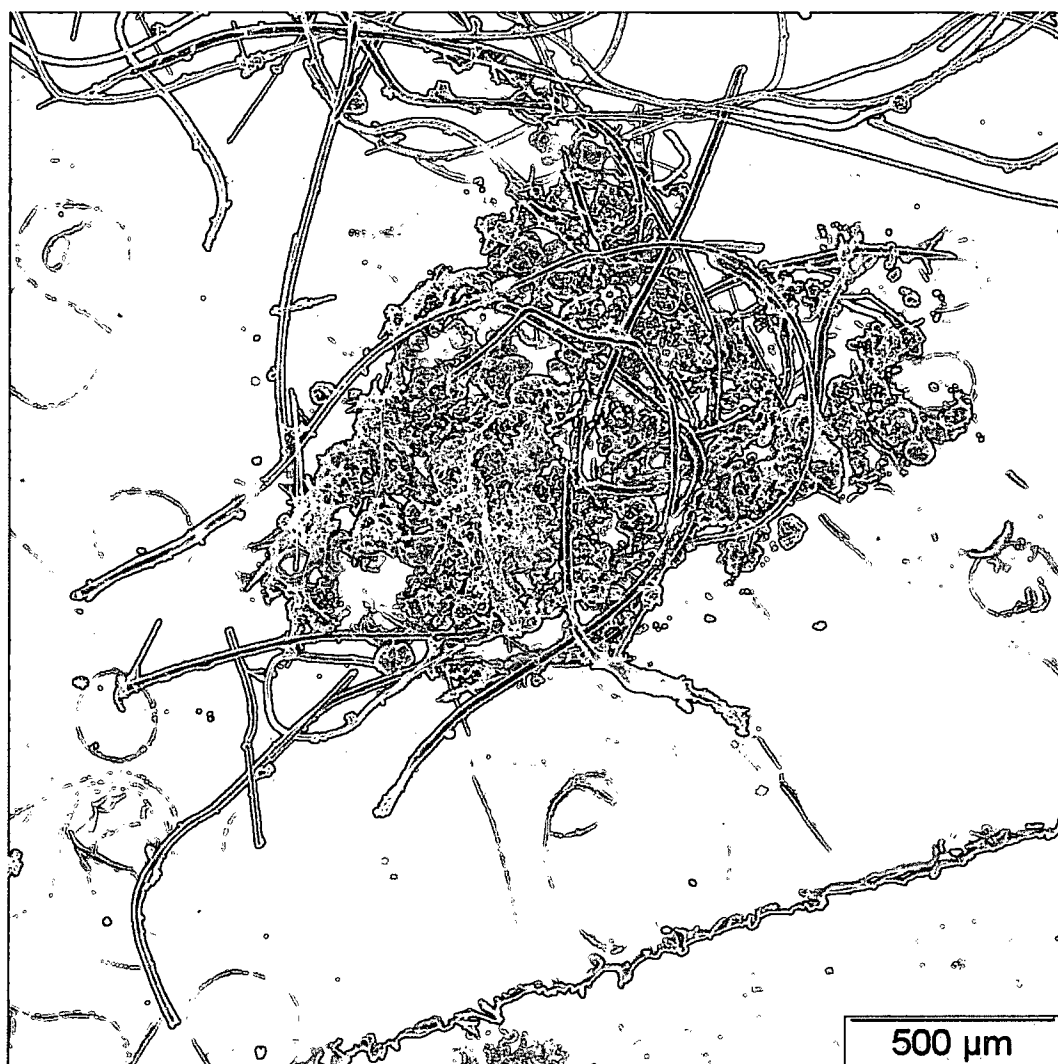


Figure 5.1-11: SEM Image of 3M Interam

Low Alloy Steel

A508 Low Alloy Steel was machined from a weld mock-up used to qualify repair actions. The samples were sectioned from a large piece of material, producing coupons 1.98 x 0.5 x 3.25 cm. The coupons were then cleaned with water and ethanol, but were not polished. The coupons were reflective. Two and one-half coupons were used in each test.

An SEM/EDS analysis a coupon surface was performed. The SEM image is shown in Figure 5.1-12. The detected elements are given in Table 5.1-2.

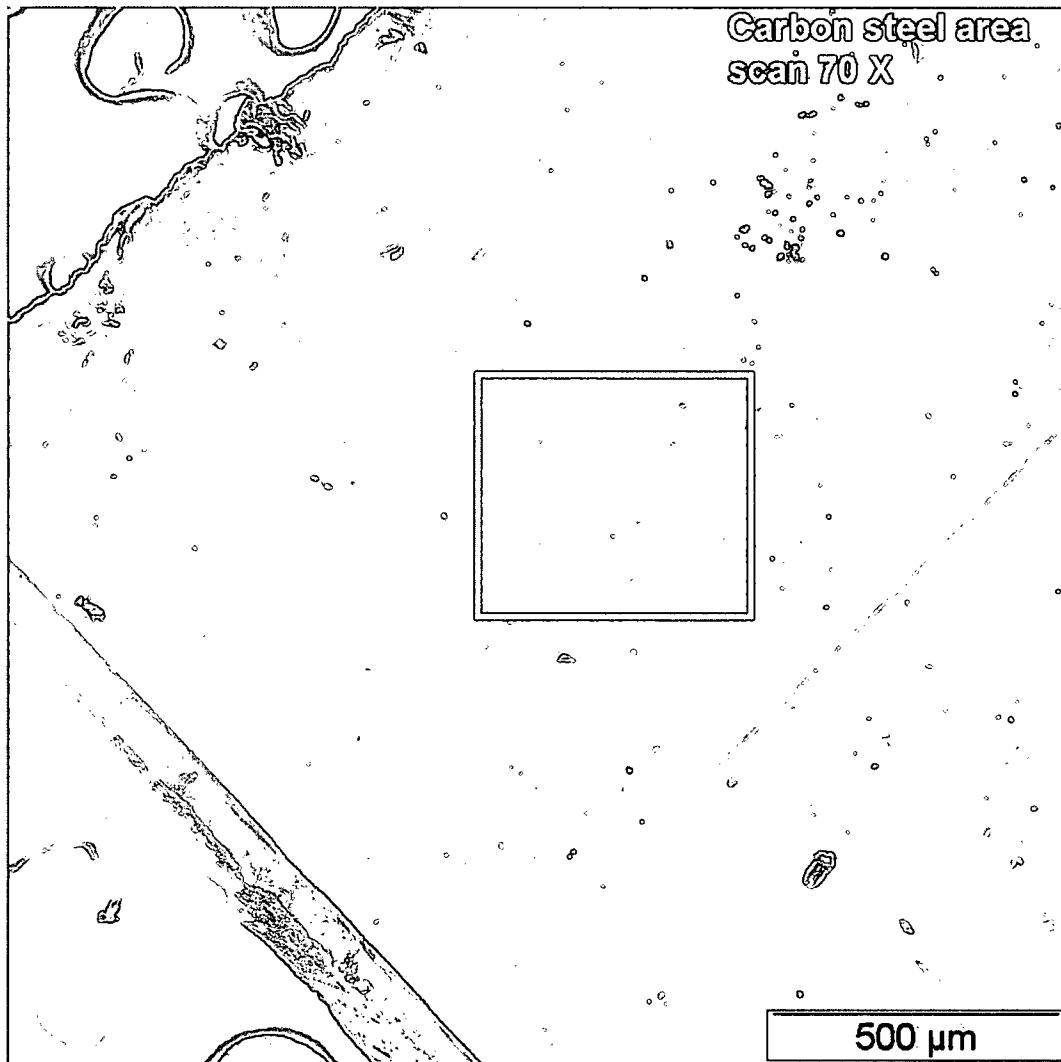


Figure 5.1-12: SEM Image of a Carbon Steel Coupon Surface

Galvanized Steel

Galvanized low carbon steel sheet 0.032 inches thick was supplied by McMaster Carr (Part Number 8943K12). The sheeting was cut with a shear into coupons that were 2.0 cm wide and 3.8 cm long. Six specimens were used in each test. The coupons were cleaned with water and ethanol, but were not polished. The coupons were reflective, suggesting that the native oxide was relatively thin.

An SEM/EDS analysis was performed on a coupon surface. The SEM image is shown in Figure 5.1-13. Only the elements aluminum, oxygen, zinc and iron were detected on the surface. Concentrations are given in Table 5.1-2.

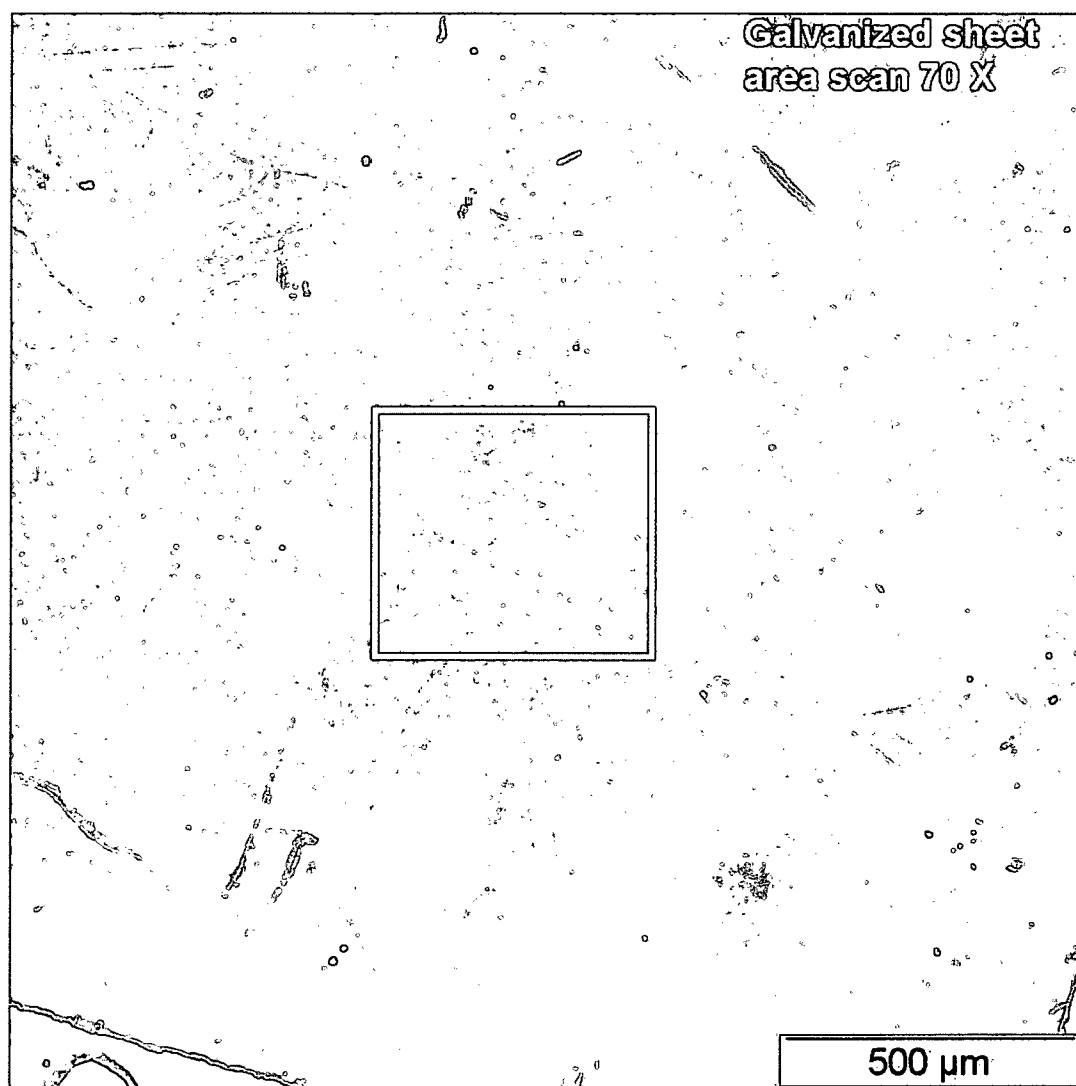


Figure 5.1-13: SEM Image of a Galvanized Steel Coupon Surface

Table 5.1-2: Elemental Composition of Tested Materials by SEM/EDS, Area Scans (Wt%)

Material	Weight Percent														
	C	O	Mg	Al	Si	S	K	Ca	Fe	Na	Mn	Ti	Cr	Ni	Zn
Aluminum				99.57					0.43						
Concrete	30.46	46.59	0.65	2.45	6.74	0.58	0.29	11.87	0.36						
CalSil	27.99	41.31	0.29	2.24	11.50		0.46	14.08	0.87	1.25					
Nukon	26.65	46.26	0.82	1.43	14.39		0.33	2.95	0.15	6.98	0.03				
High Density Fiberglass	59.03	31.17	0.26	0.42	5.09	0.29	0.14	1.07	0.13	2.41					
Mineral Wool	34.80	38.13	3.21	3.49	8.90		0.14	8.81	1.92	0.36	0.08	0.15			
MIN-K	38.33	51.08		0.81	7.48			1.49				0.81			
Fiber Fax Durablanket	33.05	45.78		11.27	9.91										
Interam	40.65	49.01		8.67	1.46			0.21							
Carbon Steel				1.53	0.35	0.80			95.51		0.89		0.43	0.50	0.50
Galvanized Steel		6.29		3.20					1.62						88.98

Table 5.1-3 Normalized Elemental Composition- Carbon and Oxygen Removed (Wt%)

Material	Normalized Weight Percent												
	Mg	Al	Si	S	K	Ca	Fe	Na	Mn	Ti	Cr	Ni	Zn
Aluminum		99.6					0.4						
Concrete	2.8	10.7	29.4	2.5	1.3	51.7	1.6						
CalSil	0.9	7.3	37.5		1.5	45.9	2.8	4.1					
Nukon	3.0	5.3	53.1		1.2	10.9	0.6	25.8	0.1				
High Density Fiberglass	2.7	4.3	51.9	3.0	1.4	10.9	1.3	24.6					
Mineral Wool	11.9	12.9	32.9		0.5	32.6	7.1	1.3	0.3	0.6			
MIN-K		7.6	70.6			14.1				7.6			
Fiber Fax Durablanket		53.2	46.8										
Interam		83.8	14.1			2.0							
Carbon Steel		1.5	0.3	0.8			95.0		0.9		0.4	0.5	0.5
Galvanized Steel		3.4					1.7						94.9

5.1.2.2 Material Amounts Added

The material additions were scaled to the chemical reactor volume. Table 5.1-4 below presents the amount of material added for a 100 ml chemical reactor volume. The amounts were scaled to maintain a given material-to-coolant volume ratio, specified in terms of surface area of material to coolant volume or material volume to coolant volume. The target ratios were the maximum ratios from Table 3.1-1 reported in the industry survey. For the dissolution experiments, the material was measured by mass for fibrous materials as a matter of convenience, with material densities being used to convert between volume and mass. The material densities with the exception of concrete are obtained from Table 3-2 of Reference 5.1-5.

Table 5.1-4: Target Material Additions

Material	Material/Coolant Ratio		Assumed Density (lb/ft ³)	Target Addition for 100 ml solution	
	Value	Units		Mass (g)	Surface Area (cm ²)
Fiberglass Insulation Max Ratio	0.14	ft ³ /ft ³	4	0.900	
Cal Sil Insulation Max Ratio	0.18	ft ³ /ft ³	14.5	4.180	
Min-K Max Ratio	0.001	ft ³ /ft ³	16	0.026	
Mineral Wool Max Ratio	0.04	ft ³ /ft ³	10	0.640	
DuraBlanket	0.0213	ft ³ /ft ³	12	0.410	
Interam Only Ratio	0.00027939	ft ³ /ft ³	60	0.027	
Aluminum Max Ratio	5.42	ft ² /ft ³			17.8
Carbon Steel Max Ratio	10.78	ft ² /ft ³			35.4
Zinc Max Ratio	27.98	ft ² /ft ³			91.8

The concrete addition was not scaled to any value derived from the industry survey because exposed concrete in containment is typically expressed in surface area, and the surface area of the crushed concrete that was supplied was not known when the tests were begun. A value of 4.0 g/100 ml was chosen arbitrarily. Later measurements of the concrete surface area indicated that only 0.0002 g of the powder was needed to maintain the desired material to coolant ratio of 4.79 ft²/ft³. The concentrations of calcium due to dissolution of concrete obtained in the dissolution tests were much higher than would be actually observed and, in this sense, the amount of concrete used was highly conservative. However, the degree of conservatism in the model calculations is not directly related to the concrete to coolant ratio, and the amount of concrete used was suitable for use in model development.

5.1.3 References

- 5.1-1 J. Oras, J. H. Park, K. Kasza, K. Natesan, and W. J. Shack, "Chemical Effects/Head-Loss Testing Quick Look Report, Tests 1&2, September 16, 2005, NRC IN 2005-26 PT2.

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- 5.1-2 V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.
- 5.1-3 J. C. Griess and A. L. Bacarella, "Design Considerations of Reactor Containment Spray Systems-Part III. "The Corrosion of Materials in Spray Solutions", Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.
- 5.1-4 PWR Primary Water Chemistry Guidelines: Volume 2, Revision 5, EPRI, Palo Alto, CA: 2003. TR-105714-V2R5.
- 5.1-5 NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

5.2 DISSOLUTION AND PRECIPITATION TESTS

The testing described in this section was meant to develop information to supplement and augment the information obtained from the PWR Industry "Integrated Chemical Effects Test" (ICET) program that looked at chemical reactions that can occur in PWR containments after a loss of coolant accident. In five (5) tests, the ICET program examined the long-term chemical reactions and the associated chemical reaction products that may occur in a simulated containment sump environment. The ICET program tests were performed using two (2) types of thermal insulation materials and three (3) pH buffer agents.

The dissolution and precipitation tests performed during this program were done at a smaller "bench level" scale. The primary objective of the current program was to examine more insulation materials in different pH boric acid solutions over a wider range in temperature, focusing on high temperatures that may be present at the early stages of a LOCA. The testing examined dissolution of insulation materials and potential precipitate reactions that may affect performance of containment sump screens. This simplified "bench level" plan allowed a large number of tests to be completed in a time and cost effective manner.

5.2.1 Functional Requirements

The functional requirements listed below were used to guide the design and construction of the dissolution apparatus and the equipment used for precipitation characterization.

The chemical reaction apparatus must be able to measure:

1. The dissolution rates of various containment materials when contacted with simulated solutions
2. The characteristics of precipitates that form in the coolant solutions after dissolution of containment materials followed by changes in temperature and/or chemistry. The characteristics to be measured are:
 - Precipitate Mass
 - Precipitate Settling Rate

- Precipitate Volume
- Precipitate Filtering Characteristics

These high level functional requirements translate into the following equipment requirements:

Reaction Vessel

1. Must be chemically inert over the temperature range of 70°F to 270°F.
2. Must be able to withstand pressures up to 21 psig at 270°F. (Note: This is necessary so that the solution design temperature can be held at the maximum temperature without boiling away. The vapor pressure of water at 270°F is 35.4 psia. Thus, the differential pressure across the reactor will be 35.4-14.7 psia = 20.7 psig)
3. Must have means for introduction of sample coupons and removal after the test.
4. The temperature equilibrium within the vessel must occur ($\pm 5^\circ\text{F}$) within 10 minutes of test initiation (contact between the solution and containment material). This is required because short term dissolution rates are being measured. Samples will be taken at 15 to 30 minute intervals.
5. Must have a means for mixing/stirring

Heating System

1. Must be capable of achieving a maximum temperature of at least 270°F.
2. Must be capable of controlling temperature within a band of $\pm 5^\circ\text{F}$.

Cooling System

1. Must be capable of achieving a minimum temperature of at least 70°F.
2. Must be capable of controlling temperature within a band of $\pm 5^\circ\text{F}$.

Fluid Transfer System

The fluid transfer system must:

1. Transfer fluid to and from the reaction vessel.
2. Be chemically inert over the temperature range of 70°F to 270°F.
3. Withstand pressures up to 21 psig at 270°F.
4. Not release pump wear particles.
5. Provide a means for withdrawing solution samples.
 - Solution withdraw must not remove particulate containment materials being tested.
 - Solution samples must be at least 2.5 ml for ICP analysis with 5.0 ml preferred.

-
- Samples must not be allowed to cool below 90°F during sampling.
 - The entire sample solution volume must be removed at the end of the test to stop the reaction.
6. Keep temperature above 90°F until discharge into sample vessel or settling cone.
 7. Transfer samples at a rate such that the sampling time is short relative to the test time (5 ml within 2 minutes).
 8. Minimize cross contamination between samples.
 - Tubing runs should be as short as possible.
 - Tubing should be clear to detect deposit formation within the lines.
 - A means for flushing the tubing between samples should be provided.

Sample Bottles

1. Minimum volume - 5 ml (to allow for one analysis and a repeat)
2. Will not react with the stored solution
3. Must withstand an initial temperature of at least 90°F.
4. Must have a closure that prevents evaporation.

Settling Cone

1. Must withstand a temperature of 90°F.
2. Must have a conical base to increase sensitivity.
3. Must be transparent.
4. Must have a cap to prevent evaporation during settling.
5. Must have a diameter greater than the largest particles expected.
6. Must have graduations so that both the volume of solution and the volume of precipitate can be measured.

Filtration System

1. Must have a means for measuring the pressure across the filter with a resolution of 0.1 psi or better.
2. Must be able to quantitatively transfer the precipitated material to a filter membrane or membranes that can be weighed to determine mass gain.
3. The membrane should remove a particle size fraction similar to that removed by a fibrous bed on a sump screen.
4. The flow rate across the screen should be variable so that the particles can be characterized by their pressure drop verses flowrate curve.

-
5. The filtration system must withstand the test solutions at a temperature of 90°F without degradation (especially the release of particulates).

5.2.2 Dissolution Tests

Dissolution testing was performed using a series of reaction vessels and solution reservoirs housed in a mid-sized air furnace. The test matrix listing the dissolution tests performed is given in Table 4.2-1. A schematic of the equipments used is shown in Figure 5.2-1 and several photographs showing various features of the equipments are shown in Figures 5.2-2 through 5.2-5.

5.2.2.1 Test Preparation

All test solutions were prepared using reagent grade chemicals including boric acid and sodium hydroxide mixed in deionized water having a starting conductivity < 1 uS/cm. The PWR containment materials tested include: aluminum, FiberFrax, Cal-Sil, carbon steel, concrete, Nukon, other fiberglass, Min-K, Interam, Min-Wool, and zinc.

These materials were either purchased from an appropriate vendor or supplied directly by sponsor utility members. For each material tested, the coupon size was scaled to the volume or surface area for that material in containment using US plant survey data. The coupons were cut to have that appropriate volume or surface area.

Coupons were weighed and measured to determine the starting mass and surface area or volume. All metallic coupons were cleaned and dried.

The first step in the actual testing was to fill the solution reservoirs with the appropriate pH boric acid solution and place that reservoir into the furnace. The solution reservoirs were equipped with pressure relief valves to allow elevated temperature testing under safe operating conditions. The pressure relief valves were set to release if the pressure in the reservoir exceeded the saturation pressure of the test solution at the target test temperature by a minimum of 10 psi. The solution in the reservoir was then heated.

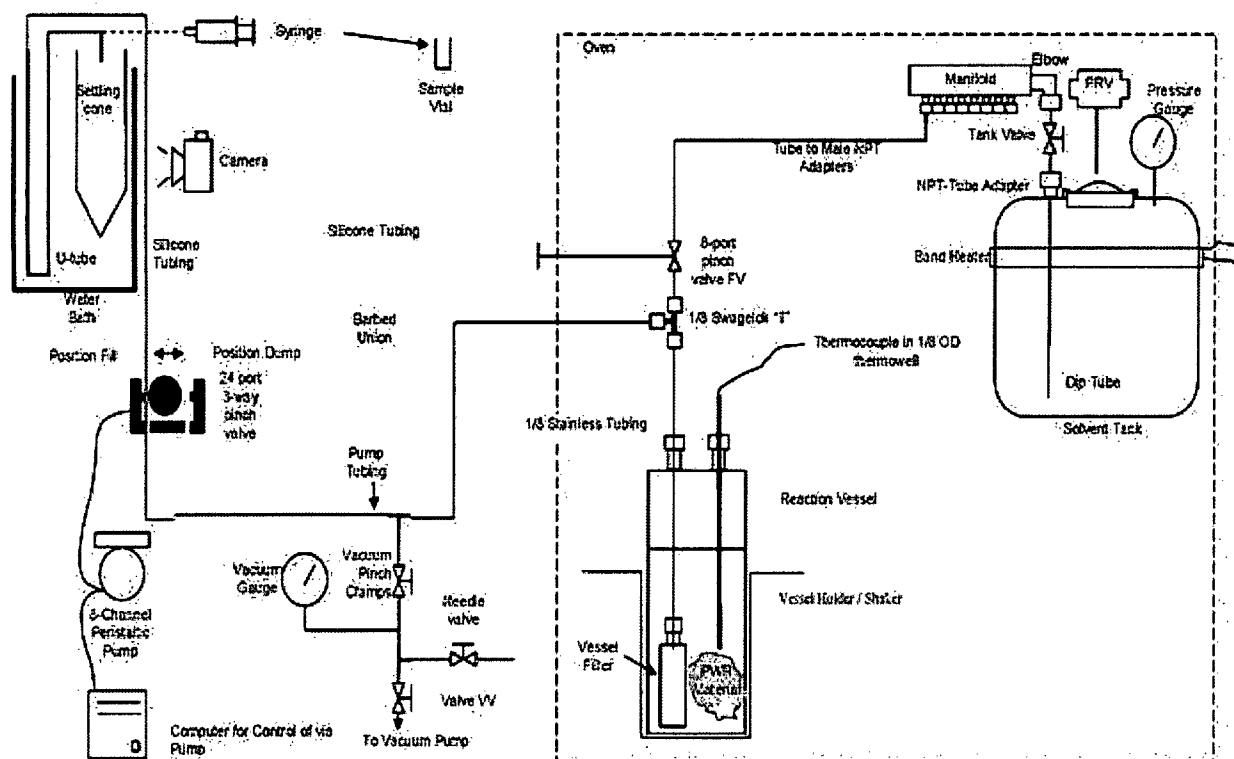


Figure 5.2-1: Bench Tests Equipment Schematic

The solution reservoirs were placed in the oven shown in Figure 5.2-2 and heated. Figure 5.2-3 shows two reservoirs in the back of the furnace. The test solution was distributed by a manifold and directed to one of eight reaction vessels in the furnace that contained the materials to be tested. The reaction vessels are shown in Figures 5.2-4 and 5.2-5. For initial testing at 190°F, Teflon reaction vessels were used. Problems with reliability, especially for testing conducted at 265°F, necessitated switching to stainless steel reaction vessels. In either case, each reaction vessel was equipped with an inlet/outlet tube and a thermowell containing a calibrated thermocouple.

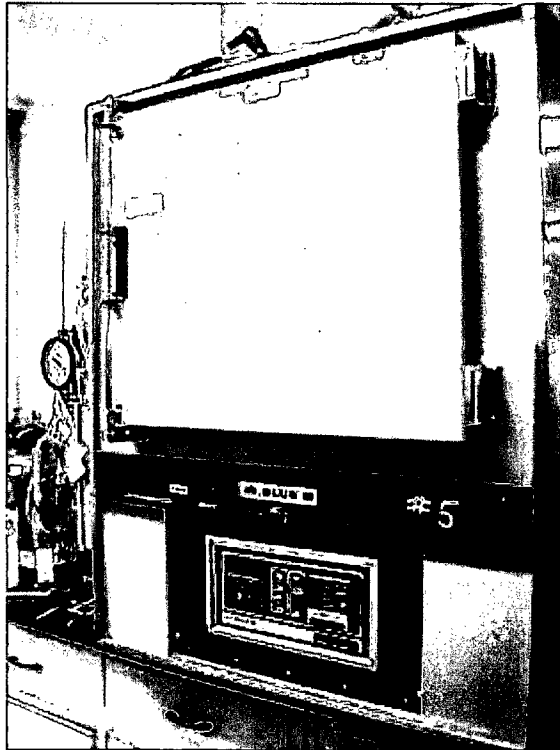


Figure 5.2-2: Oven used to contain the solution reservoirs and reaction chambers

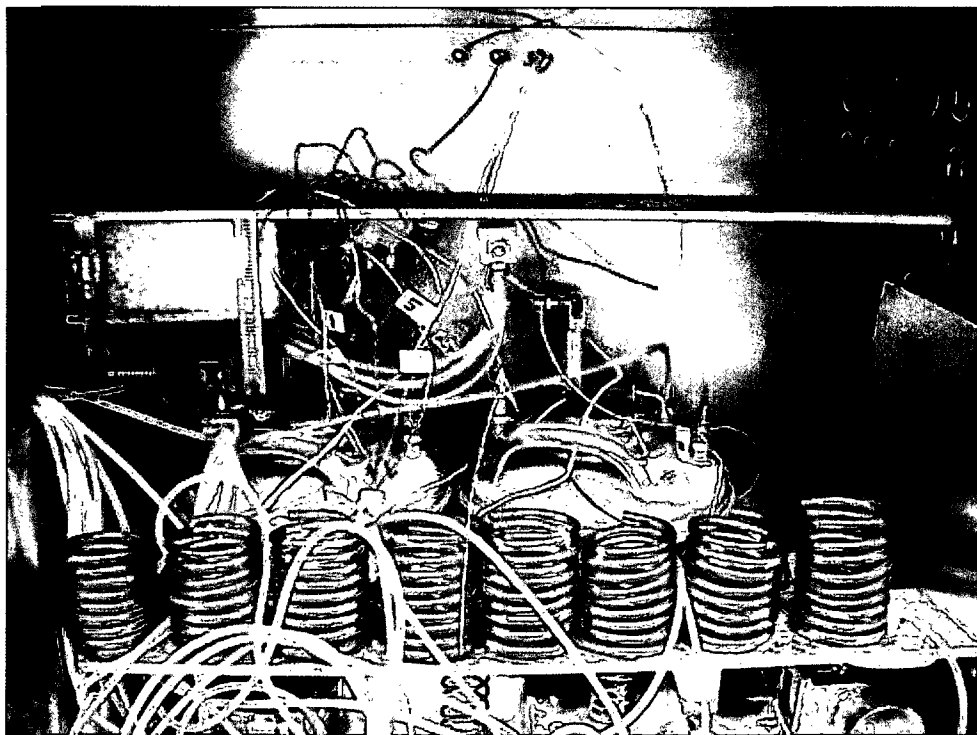


Figure 5.2-3: Photo showing two solution reservoirs inside the high temperature oven. The reaction chambers were installed in the copper coils in the foreground.

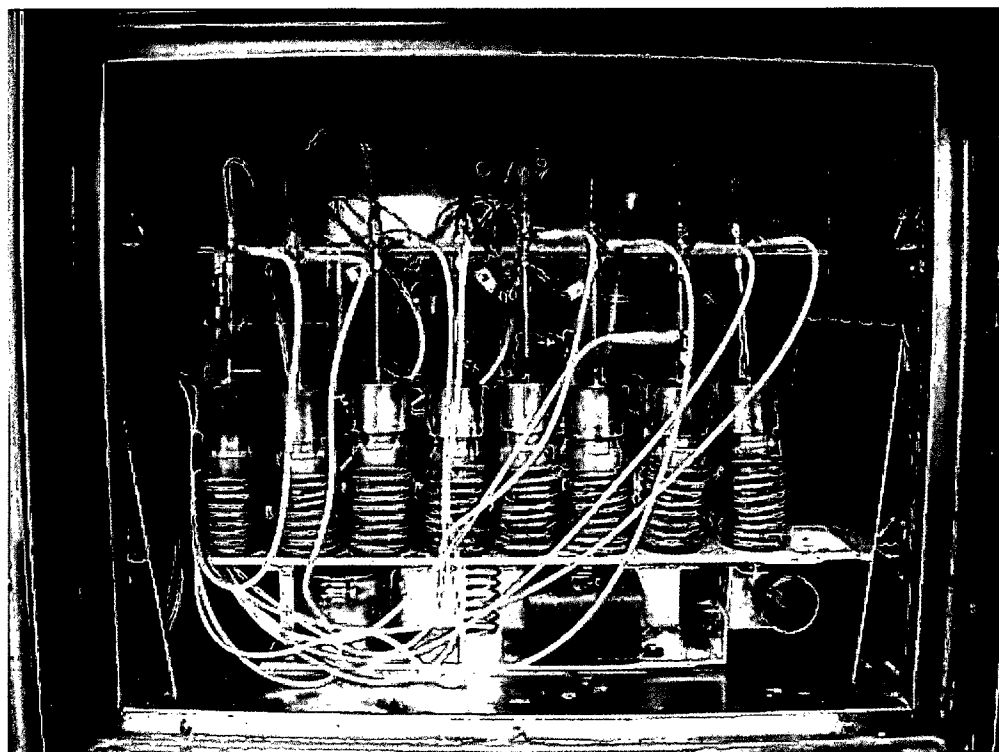


Figure 5.2-4: Eight SS reaction chambers within the oven located on a rocking platform.

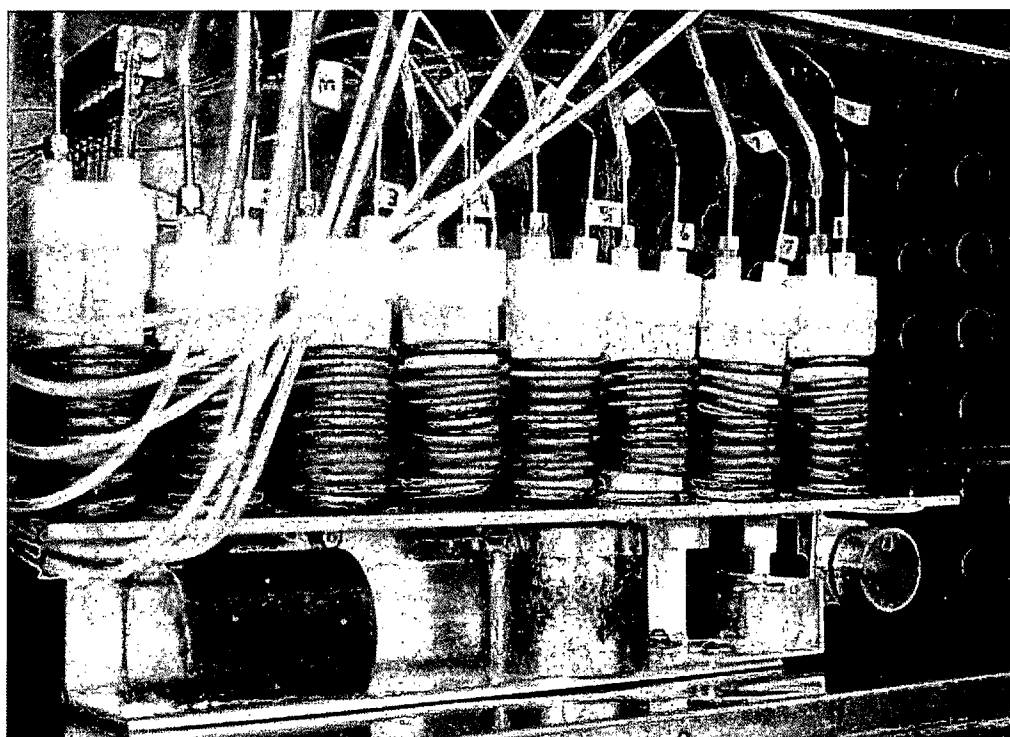


Figure 5.2-5: Teflon reaction vessels were used for many of the experiments at 190°F. Problems with reliability at higher temperatures led to switching to stainless steels vessels.

One test material was placed in each reaction vessel. Typical quantities are shown in Figure 5.2-6. A fresh filter was placed in the reaction chamber to prevent removal of the test materials during solution transfer. The reaction vessels were sealed in place and pressure tested to 60 psig. The appropriate lines were connected and each reaction vessel was placed on a shaker mechanism.

The oven was then heated to temperature. A band heater attached to the solution reservoir allowed the solution to reach test conditions more rapidly. As the oven was heated, temperatures were measured including:

- Furnace temperature
- Temperature of the solution reservoir
- Temperature in each reaction vessel

All thermocouples readings were recorded using a data acquisition system using reading intervals from 3 to 10 seconds.

Pressures were also measured in the solution reservoir and the lines with a combination of pressure gauges and pressure transducers as shown in Figure 5.2-7. The test chambers were initially evacuated and when the test solution reached the target test temperature, the experiments were initiated.

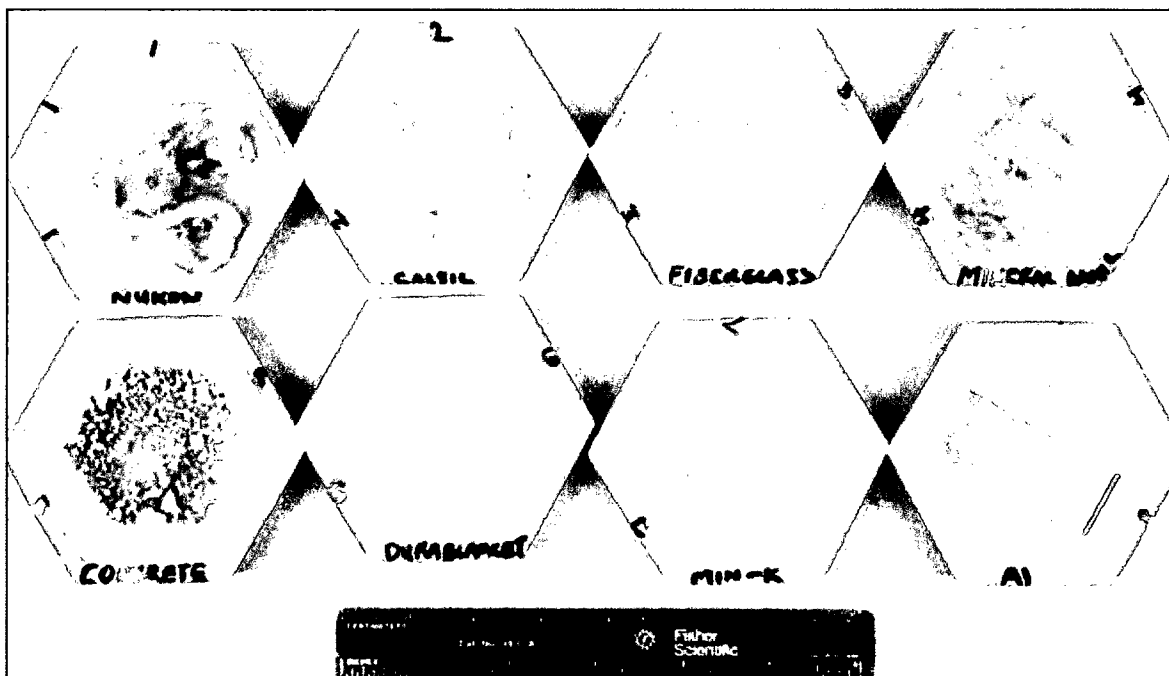


Figure 5.2-6: Representative Tested Material Amounts

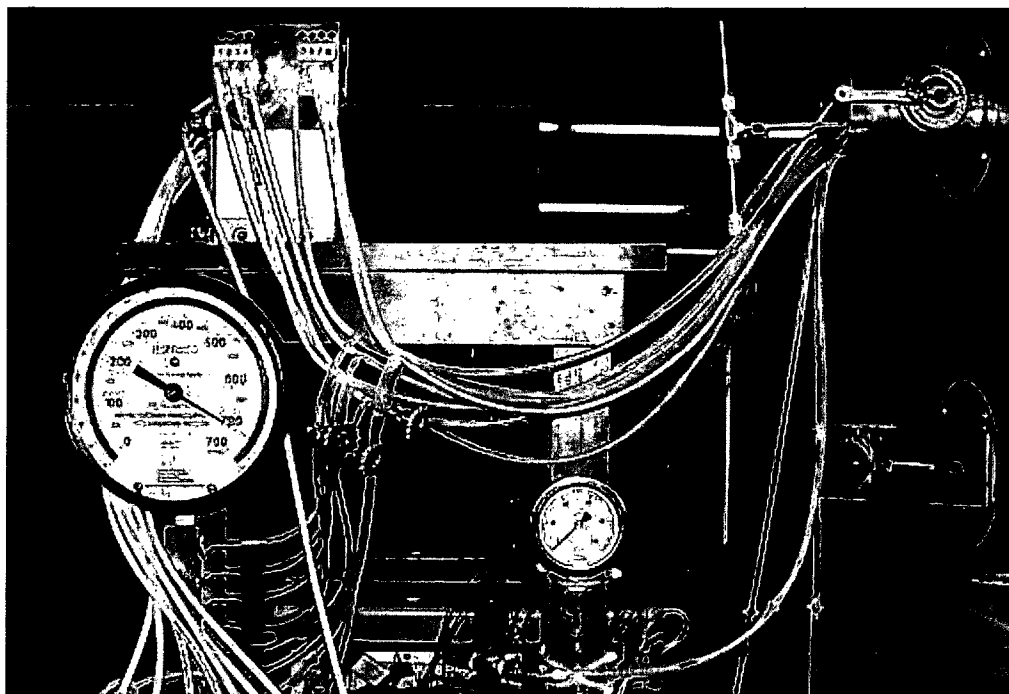


Figure 5.2-7: Pressure gauges and computer operated pinch valve used to control flow and monitor test conditions.

5.2.2.2 Test Procedure

Solution temperatures, pressures and flow rates were measured using the equipment shown in Figure 5.2-8 and Figure 5.2-9. When the temperatures of the solution reservoir and reactors were within acceptable ranges, the 8 port pinch valve to fill the reactor vessels was opened and the computer program used to time the sampling operation was started. At appropriate times, the computer program initiated a flush operation on all lines between the reaction vessel and the water bath containing the settling cones. The flush volume was at least equal to the internal line volume. The boric acid flush solutions flowed into syringes for measurement and disposal. Once an appropriate amount of solution was flushed, the lines were connected to a second series of syringes with plunger stops set to 5 ml. The computer program then opened a 24 port valve to fill syringes. When the syringes were filled, the 24 port valve was closed, and the syringe solutions transferred to pre-labeled sample vials. The samples were sent to Industrial Analytical, Inc. for chemical analysis using ICP-MS, Inductively Coupled Plasma Mass Spectrometry, to determine how much of the PWR test material dissolved into the boric acid solution at that point in time.

At the next sampling time, the process was repeated. Sampling was performed at 0.5, 1 and 1.5 hours. One additional sampling time was sometimes used.

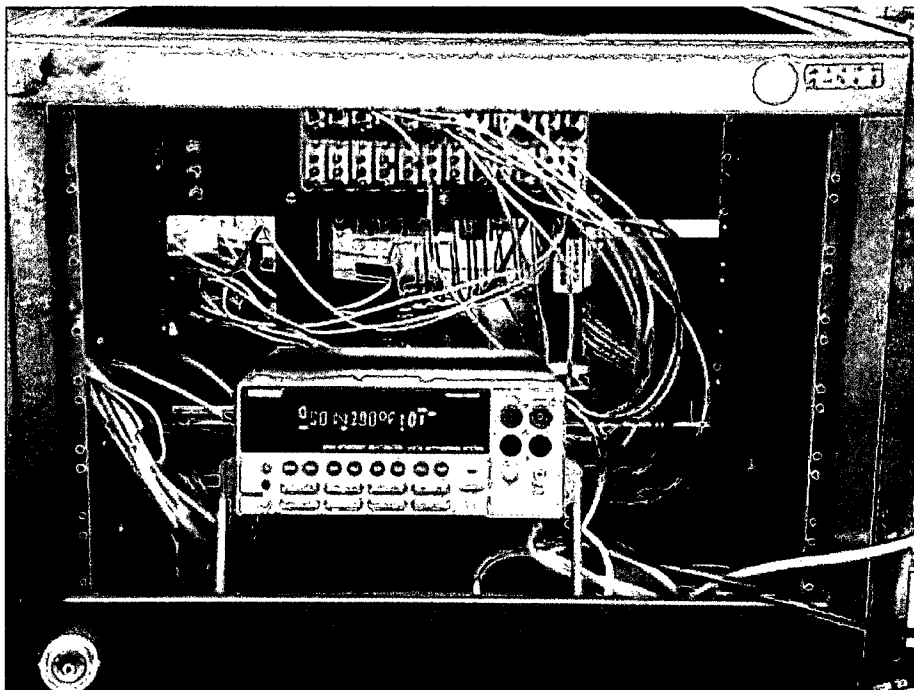


Figure 5.2-8: PC controlled voltmeter used to measure temperature, pressure and flow rates.

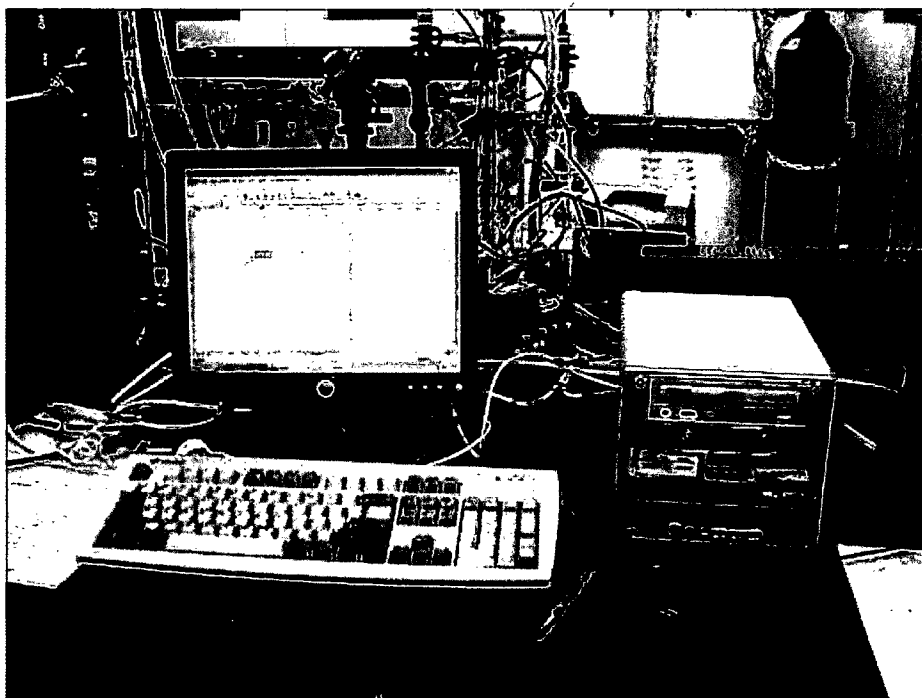


Figure 5.2-9: Data acquisition system used to record test parameters and control valves and pump during the dissolution and precipitation phases of the experiment.

5.2.3 Results of Dissolution Tests

The tests were performed as described in the test matrix in Table 4.2-1. Nineteen runs using the dissolution apparatus were made (Runs A through S). With multiple materials being tested in most of the runs, a total of 140 material dissolution tests were performed along with two blank runs. Of the 140 dissolution tests, 52 were rejected because of failure to maintain temperature within the target range or fluid control failures. Concentrations of dissolved chemical species, release rates, and sample mass measurements are given in Appendix A. Of the 88 good runs, only 66 were needed to satisfy the design matrix and these are referred to as “design matrix tests” in the discussion. The other 22 runs were considered replicates. The replicate runs were included in model development to aid in error estimation and to improve the confidence interval for model predictions.

The ICP analyses included analyses for Al, Ca, Si, Mg, P, S, Fe, Zn, and Ti. The values obtained for P, Mg, and Ti were negligible and can be ignored in any chemical effects head loss testing.

The total mass of each element release in the design matrix dissolution tests was calculated by summing the releases for all times, temperatures, and pH levels. The releases included all of the materials tested. The results are shown in Table 5.2-1 and Figure 5.2-10. Aluminum, silicon, and calcium dominated the release.

Table 5.2-1: Comparison of Total Mass Release in Dissolution Testing by Element

Element	Total Mass Released into Solution (mg)
Fe	3
Zn	3
S	25
Ca	110
Si	393
Al	1634

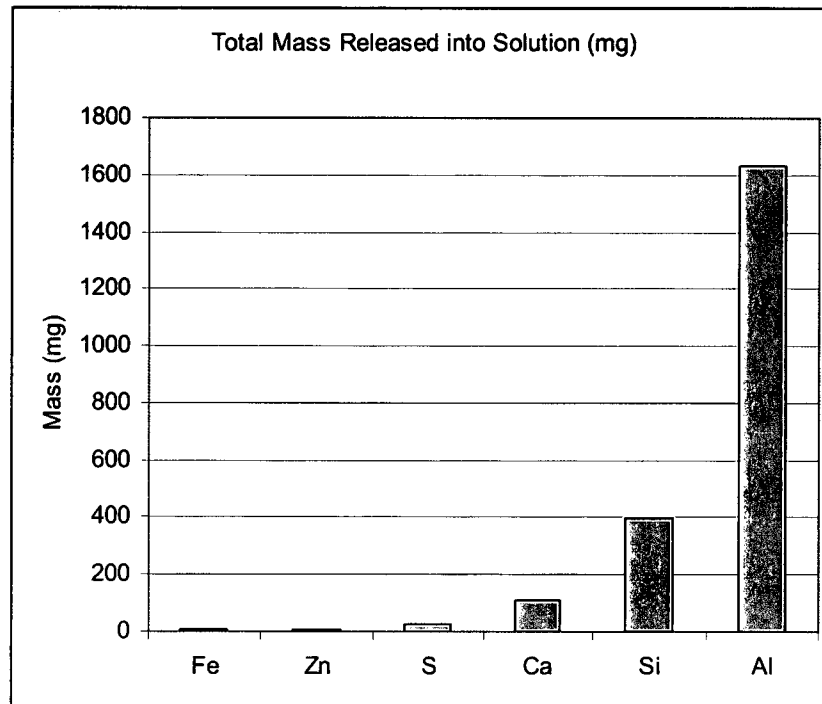


Figure 5.2-10: Comparison of Total Mass Released during Dissolution Testing by Element

The releases from each material were calculated from the test data, and the results are compared in Table 5.2-2 and Figure 5.2-11. It is clear that metallic aluminum has the highest potential for mass release into solution. The concrete release appeared to be relatively high, but the quantity of concrete tested was not scaled to the surface area typically present in PWR containments as were the other materials. This value would have been much lower if had been scaled correctly to the plant survey data provided. Of the insulation materials that were considered, CalSil had the highest potential release and mineral wool the lowest. It is notable that the high density fiberglass released more material than did the Nukon fiberglass.

Table 5.2-2: Comparison of Total Mass Release from the Tested Materials

Material	Total Mass Released into Solution (mg)
Carbon Steel	6
Galvanized Steel	8
Mineral Wool	18
Interam	31
Durablanket	34
Nukon Fiberglass	55
MIN-K	69
High Density Fiberglass	92
CalSil	177
Concrete	376
Aluminum	1580

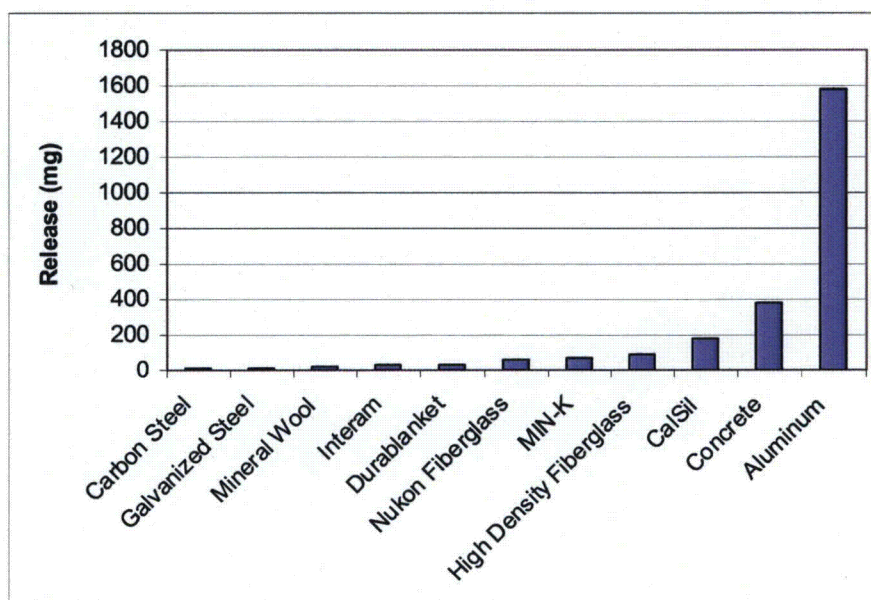


Figure 5.2-11 Comparison of Total Mass Release from the Tested Materials

The variation in calcium and aluminum release with pH was explored. The total Al and the total Ca release was calculated for all design matrix runs at each pH. The values are plotted in Figure 5.2-12. Opposite trends were observed, with more calcium being released at low pH and more aluminum being released at high pH.

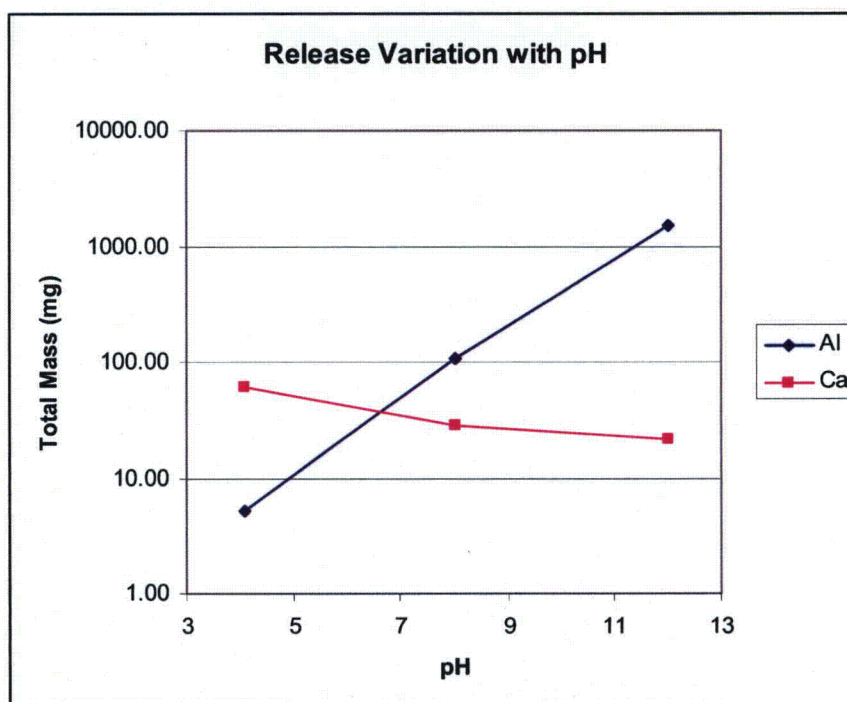


Figure 5.2-12: Total Release of Al and Ca from all Materials over pH Range

5.2.4 Precipitation Tests

5.2.4.1 Test Apparatus and Procedure

At the completion of the 1.5 hour experiments in the reaction vessels, the remaining solutions were pumped into settling cones to measure any precipitation caused by cooling of the dissolved solution. Specifically, the hot test solutions were pumped through small diameter stainless steel cooling lines in a constant temperature water bath and into the settling cones. A timer was started and the material in the settling cones was examined at appropriate intervals. At approximately 30 minutes, cones with any precipitate were noted and photographed. After approximately 1 hour, this process was repeated. After at least 8 hours after the solution was admitted into the settling cone, photographs of the cones were taken, and the presence of any visible precipitates noted.

Figure 5.2-13 shows the settling cones in the water bath. The bath temperature was maintained at 80°F using a combination of heaters and coolers. The small diameter stainless lines used to cool the solution coming from the oven are shown in the background.

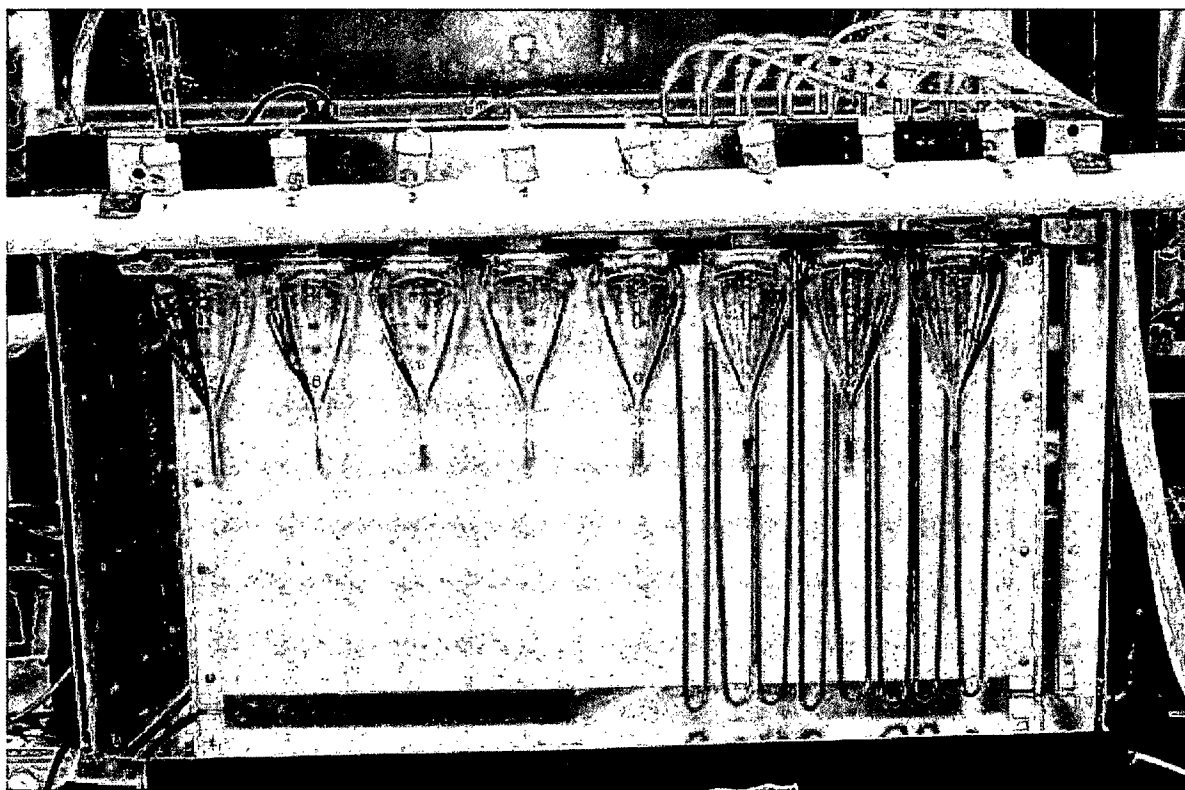


Figure 5.2-13: Solution flowed from the reaction vessels and was cooled in a water bath controlled at 80°F. The solution was sampled and eventually flowed into settling cones in the water bath.

5.2.4.2 Precipitation Test Matrix

The matrix for the precipitations tests performed is shown in Table 5.2-3.

The final precipitation test matrix was developed in consideration of the concentration and identification of the dissolved species detected from dissolution testing. Evaluation of these data indicated that the form and quantity of the key precipitates that would form from species dissolved at elevated pH (>9.0), i.e., sodium aluminum silicate and aluminum oxyhydroxide, would not be fundamentally affected by slight increases in pH. Additionally, the form and quantity would not be expected to fundamentally change as a result of the direction of the change in pH.

Fresh trisodium phosphate was used in all phosphate precipitation tests. Testing on the dissolution rate of aged versus fresh trisodium phosphate showed that aging has only a marginal effect on the dissolution rate of trisodium phosphate⁵. Therefore, the condition of the trisodium phosphate used for precipitation testing would not be expected to have any effect on the quantity and morphology of the phosphate precipitates evaluated in this testing.

Table 5.2-3: Precipitation Test Matrix

PPT Run	Run/ Reaction Vessel	Solution A	Solution B		Precipitation Method
		Dissolution Run	Dissolution Run	Buffering Agent	
1	K7	1	-	-	Precipitation from cooling, Al pH 4
2	M7	3	-	-	Precipitation from cooling, Al pH 8
3	S7	5	-	-	Precipitation from cooling, Al pH 12
4	K2	7	-	-	Precipitation from cooling, CalSil, pH 4
5	H2, L2	9	-	-	Precipitation from cooling, CalSil, pH 8
6	M2	11	-	-	Precipitation from cooling, CalSil, pH 12
7	K6	13	-	-	Precipitation from cooling, Nukon, pH4
8	L6	15	-	-	Precipitation from cooling, Nukon, pH 8
9	M6	17	-	-	Precipitation from cooling, Nukon, pH 12
10	K4	19	-	-	Precipitation from cooling, Other Fiberglass, pH 4
11	L4	21	-	-	Precipitation from cooling, Other Fiberglass, pH 8
12	M4	23	-	-	Precipitation from cooling, Other Fiberglass, pH 12
13	K5	25	-	-	Precipitation from cooling, Concrete, pH 4
14	L5	27	-	-	Precipitation from cooling, Concrete, pH 8
15	M5	29	-	-	Precipitation from cooling, Concrete, pH 12
16	K3	31	-	-	Precipitation from cooling, Mineral Wool, pH 4
17	H4, L3	33	-	-	Precipitation from cooling, Mineral Wool, pH 8
18	M3	35	-	-	Precipitation from cooling, Mineral Wool, pH 12
19	K8	37	-	-	Precipitation from cooling, MinK, pH 4
20	M8	39	-	-	Precipitation from cooling, MinK, pH 8
21	L8	41	-	-	Precipitation from cooling, Min K, pH 12

PPT Run	Run/ Reaction Vessel	Solution A	Solution B		Precipitation Method
		Dissolution Run	Dissolution Run	Buffering Agent	
22	O4, K4	43	-	-	Precipitation from cooling, FiberFax, pH 4
23	L1	45	-	-	Precipitation from cooling, FiberFax, pH 8
24	M1	47	-	-	Precipitation from cooling, FiberFax, pH 12
25	O1	49	-	-	Precipitation from cooling, Carbon Steel, pH 4
26	N5	51	-	-	Precipitation from cooling, Carbon Steel, pH 8
27	N1	53	-	-	Precipitation from cooling, Carbon Steel, pH 12
28	O2	55	-	-	Precipitation from cooling, Galvanized, pH 4
29	N6	57	-	-	Precipitation from cooling, Galvanized, pH 8
30	N2	59	-	-	Precipitation from cooling, Galvanized, pH 12
31	O3	61	-	-	Precipitation from cooling, Interam, pH 4
32	N8	63	-	-	Precipitation from cooling, Interam, pH 8
33	N3	65	-	-	Precipitation from cooling, Interam, pH 12
34	K7	1	-	TSP pH 8	PPT of Phosphates, Aluminum
35	K2	7	-	TSP pH 8	PPT of Phosphates, CalSil
36	K6	13	-	TSP pH 8	PPT of Phosphates, Nukon
37	K4	19	-	TSP pH 8	PPT of Phosphates, Other Fiberglass
38	K5	25	-	TSP pH 8	PPT of Phosphates, Powdered Concrete
39	K3	31	-	TSP pH 8	PPT of Phosphates, Mineral Wool
40	K8	37	-	TSP pH 8	PPT of Phosphates, MinK
41	O4	43	-	TSP pH 8	PPT of Phosphates, FiberFax
42	O1	49	-	TSP pH 8	PPT of Phosphates, Steel
43	O2	55	-	TSP pH 8	PPT of Phosphates, Galvanized
44	O3	61	-	TSP pH 8	PPT of Phosphates, Interam
45	K7	1	-	Borax pH 8	PPT of Hydroxides, Aluminum
46	K2	7	-	Borax pH 8	PPT of Hydroxides, CalSil
47	K6	13	-	Borax pH 8	PPT of Hydroxides, Nukon
48	K4	19	-	Borax pH 8	PPT of Hydroxides, Other Fiber Glass
49	K5	25	-	Borax pH 8	PPT of Hydroxides, Concrete
50	M1	31	-	Borax pH 8	PPT of Hydroxides, Mineral Wool
51	K3	37	-	Borax pH 8	PPT of Hydroxides, MinK
52	K8	43	-	Borax pH 8	PPT of Hydroxides, Fiberfax
53	O4	49	-	Borax pH 8	PPT of Hydroxides, Steel
54	O1	55	-	Borax pH 8	PPT of Hydroxides, Galvanized
55	O2	61	-	Borax pH 8	PPT of Hydroxides, Interam
56	O3	8	5	J7 or S7	pH 4, 190°F CalSil with pH 12, 265°F Al
57	E3 or B7	26	5	J7 or S7	pH 4, 190°F Concrete with pH 12, 265°F Al
58	Q1 or E8	26	55	O2	pH 4, 190°F Concrete with pH 4, 265°F Galvanized
59	Q1 or E8	8	50	P1	pH 4, 190°F with pH 4, 190°F Carbon Steel
60	E3 or B7	23	8	E3 or B7	pH 12, 265°F Fiberglass with pH 4, 190°F CalSil

Results of initial precipitate tests, including SEM analysis results, as well as the results of previous evaluations², were used to evaluate testing of combinations that were not included in the original test plan. The conclusion of this evaluation was that no additional combinations beyond those considered needed to be tested, on the basis that the quantity of other potential precipitates would be low relative to the quantity of the key precipitates generated (e.g., zinc or other simple metal silicates, or calcium aluminum silicate or other substituted aluminum silicates).

5.2.4.3 Precipitate Formation

Widely varying amounts of precipitate were observed for individual dissolution test experiments. Figure 5.2-14 and Figure 5.2-15 show examples where varying amounts of precipitate were formed. In 25 experiments, measurable quantities of precipitate were formed. The volume of precipitate formed for these cases is shown in Figure 5.2-16.

The data indicates that in the limited cases where precipitates form, the quantity produced can vary quite widely. Table 5.2-4 shows the list of experiments where measurable precipitation occurred. This occurred in 13 of the 60 experiments performed. The mass and volume of the precipitates formed are listed in Table 5.2-4 and the precipitate density estimated.

The masses of precipitates that formed did not correlate well with the total material released, suggesting that considerable dissolved or colloidal material still remained in solution. The original intent of the precipitate mass measurements was to use the ratio of filterable to non-filterable material to reduce the amount of precipitates that would have to be considered in chemical effects screen performance testing. However, the complexity of the precipitation processes observed in this work led to the abandonment of this approach. The precipitation process was in some cases highly time-dependent, and the prediction of the ratio of dissolved and colloidal matter to that of specific precipitates that would form would require consideration of the timing of the addition of each containment material to the coolant, the change in temperature with time, and the degree and order of mixing. The revised approach used in the modeling effort assumed that all aluminum released formed a precipitate and that all calcium in phosphate solutions would precipitate, and so did not use the precipitate masses listed in Table 5.2-4.

A small portion of these precipitates were filtered and the remnant on the filter paper analyzed to attempt to determine the average precipitate composition. The compositions reported from the SEM analyses are listed in Table 5.2-5.

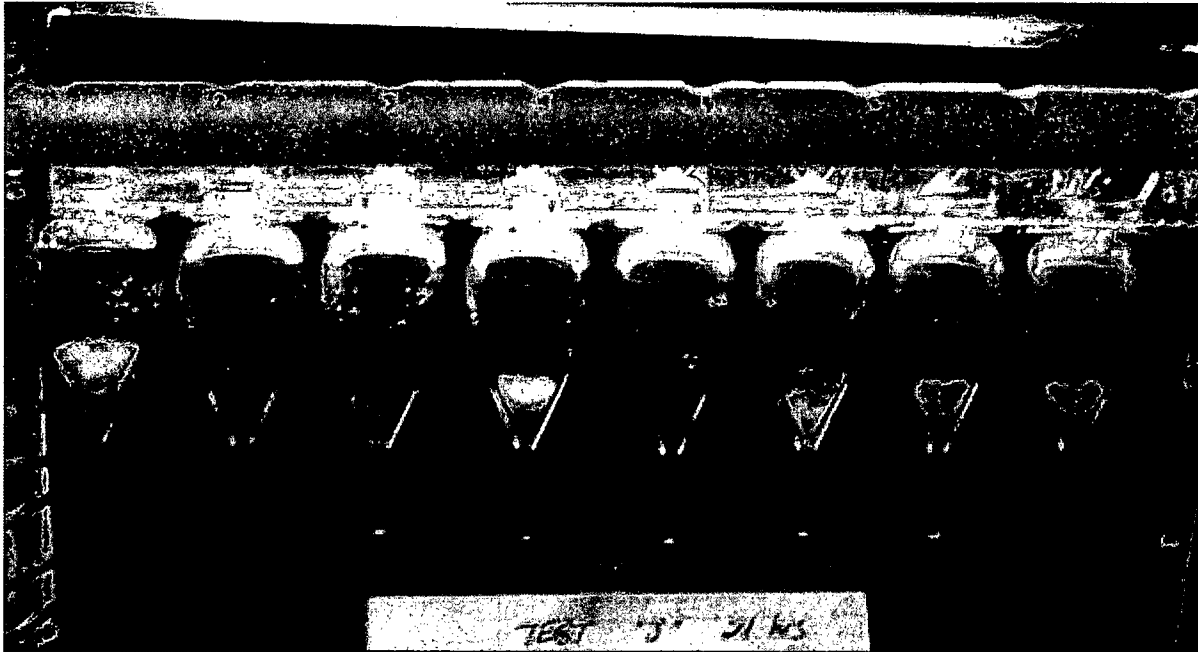


Figure 5.2-14: Appearance of the settling cones after precipitates formed in the cooled solution. Example of experiments where a significant amount of precipitates were formed.

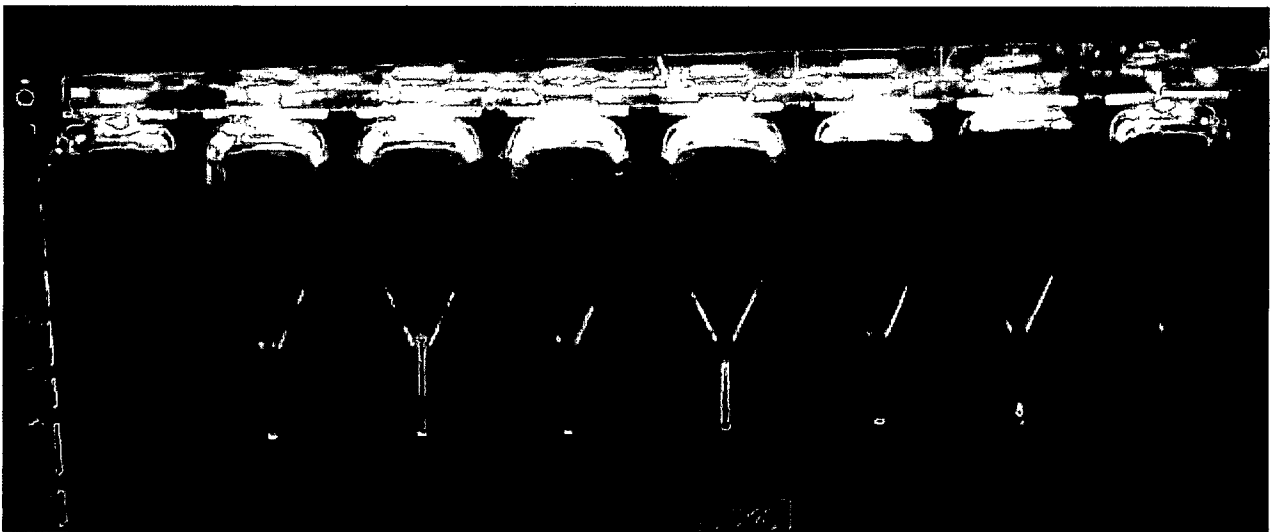


Figure 5.2-15: Appearance of the settling cones after precipitates formed in the cooled solution. Example of experiments where a moderate amount of precipitates were formed.

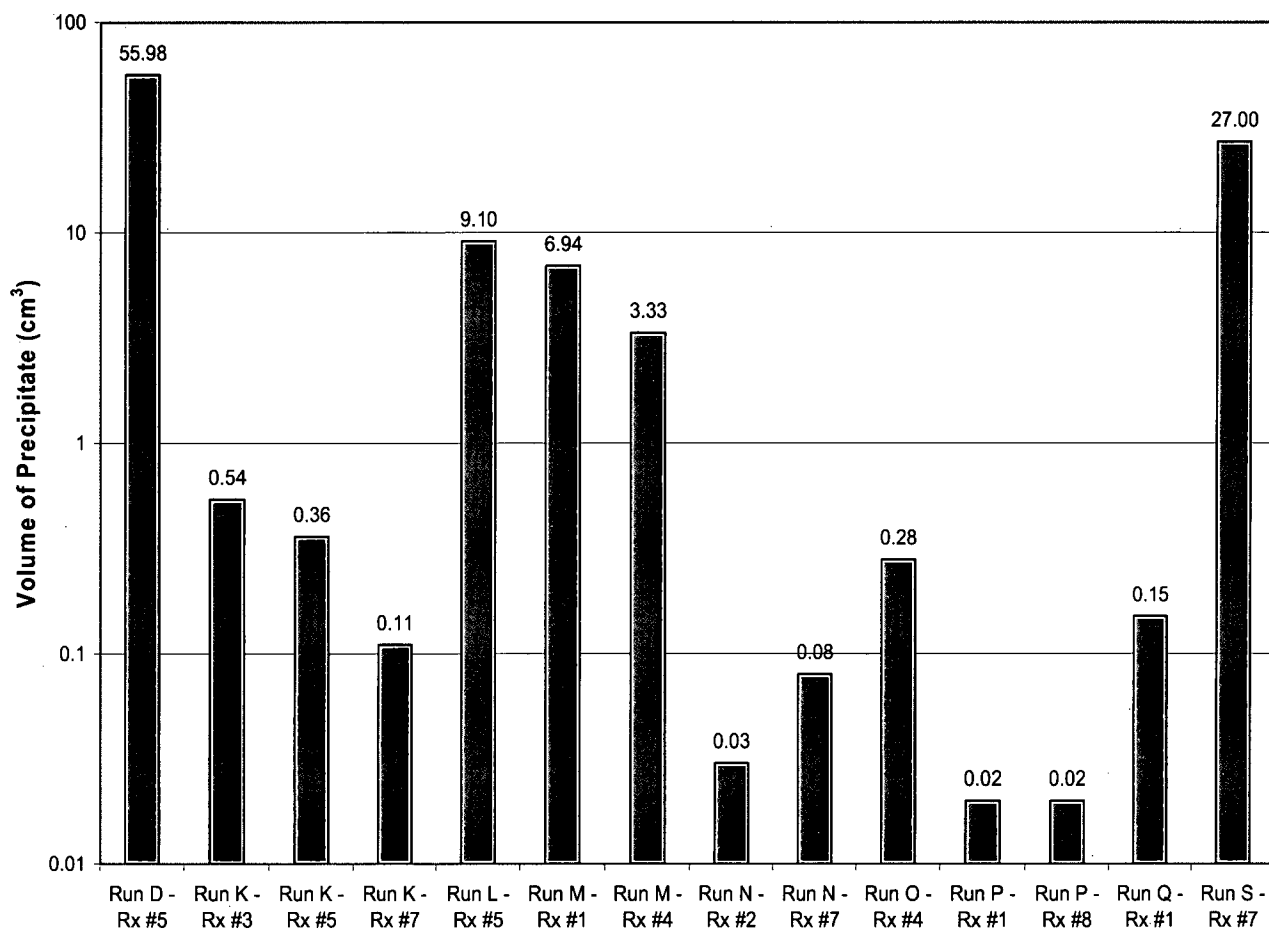
Figure 5.2-16: Volume of Precipitate Observed in the Settling Cones

Table 5.2-4: Experiments with Measurable Amounts of Precipitate

PPT Run	Run/Reactor	Dissolution Run	Material Producing Solution A	pH Solution A	Temperature Solution A	Soln B	Mass of PPT originally in cone	PPT Total Volume	PPT density	Method of Precipitation
					°F		(g)	(cm ³)	(g/cm ³)	
1	K7	1	Al	4	265	-	0.0016	0.11	0.015	Precipitation from cooling
2	N7	3	Al	8	265	-	Not measured	0.08	Not measured	Precipitation from cooling
3	S7	5	Al	12	265	-	0.6154	27	0.023	Precipitation from cooling,
12	M4	23	Other Fiberglass	12	265	-	0.0103	3.33	0.003	Precipitation from cooling
13	K5	25	Concrete	4	265	-	0.0034	0.36	0.009	Precipitation from cooling,
14	L5	27	Concrete	8	265	-	0.0375	9.1	0.004	Precipitation from cooling
16	K3	31	Mineral Wool	4	265	-	-0.0008	0.54	--	Precipitation from cooling
22	O4	43	FiberFax	4	265	-	0.0028	0.28	0.010	Precipitation from cooling
24	M1	47	FiberFax	12	265	-	0.0427	9.94	0.004	Precipitation from cooling
30	N2	59	Galvanized Steel	12	265	-	0.0045	0.03	0.151	Precipitation from cooling, Galvanized, pH 12
35	K2	7	CalSil	4	265	TSP pH 8	n/a	n/a	n/a	PPT with Phosphate
38	K5	25	Concrete	4	265	TSP pH 8	n/a	n/a	n/a	PPT with Phosphate
60	M4	23	Fiberglass	12	265	E3 (pH 4, CalSil,	n/a	n/a	n/a	Mixing of solutions from different dissolution runs
Precipitates that Formed but not in Precipitation Test Matrix										
n/a	D5	6	Al	12	190		not measured	55.98	Not measured	Precipitation from cooling
n/a	P1	50	Carbon Steel	4	190	-	not measured	0.02	Not measured	Precipitation from cooling
n/a	P8	12	CalSil	12	190	-	not measured	0.02	Not measured	Precipitation from cooling
n/a	Q1	26	Concrete	4	190	-	not measured	0.15	Not measured	Precipitation from cooling

Table 5.2-5: SEM Analysis of the Precipitates

PPT	Series/				Element (wt%)						
Run	Reacto r	Na	Al	Si	P	Ca	Cu	Zn	Fe	Mg	Best Guess PPT from Chemistry
1	K7	nd	83.1%	12.2%	nd	nd	4.7%	nd	nd	nd	Hydrated AlOOH
2	M7	2.0%	95.2%	0.0%	nd	nd	2.8%	nd	nd	nd	Hydrated AlOOH
3	S7	3.4%	96.6%	nd	nd	nd	nd	nd	nd	nd	Hydrated AlOOH
12	M4	17.3%	26.9%	53.5%	nd	2.3%	nd	nd	nd	nd	NaAlSi ₃ O ₈ with minor calcium aluminum silicate
13	K5	0.5%	74.4%	16.1%	nd	4.9%	4.1%	nd	nd	nd	Calcium aluminum silicate of some type- Al rich
14	L5	0.8%	41.6%	27.0%	nd	24.1%	5.6%	nd	0.8%	nd	Calcium aluminum silicate of some type
16	K3	0.5%	79.6%	12.7%	nd	0.1%	7.1%	nd	nd	nd	Hydrated AlOOH
22	D4	nd	85.0%	7.9%	nd	nd	7.2%	nd	nd	nd	Hydrated AlOOH
24	M1	25.3%	29.1%	38.8%	nd	nd	6.8%	nd	nd	nd	NaAlSi ₃ O ₈
30	N2	nd	1.1%	17.0%	nd	2.4%	3.7%	75.9%	nd	nd	Zn ₂ SiO ₄ (Willemite) with Ca and Al impurities
35	K2	nd	1.1%	23.5%	27.1%	43.2%	5.1%	nd	nd	nd	Calcium phosphate and a silicate
38	K5	nd	4.5%	1.0%	35.9%	54.8%	3.2%	nd	nd	0.7%	Calcium phosphate with AlOOH
60	M4	13.3%	11.1%	50.3%	nd	16.6%	8.8%	nd	nd	nd	Sodium calcium aluminum silicate

5.2.5 References

- 5.2-1 J. Oras, J. H. Park, K. Kasza, K. Natesan, and W. J. Shack, "Chemical Effects/Head-Loss Testing Quick Look Report, Tests 1&2, September 16, 2005, NRC IN 2005-26 PT2.
- 5.2-2 V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.
- 5.2-3 J. C. Griess and A. L. Bacarella, "Design Considerations of Reactor Containment Spray Systems-Part III. "The Corrosion of Materials in Spray Solutions", Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.
- 5.2-4 PWR Primary Water Chemistry Guidelines: Volume 2, Revision 5, EPRI, Palo Alto, CA: 2003. TR-105714-V2R5.
- 5.2-5 J. L. Wilken, Omaha Public Power District letter to R. C. Young, U. S. Atomic Energy Commission, dated November 14, 1973.

5.3 PRECIPITATE CHARACTERIZATION

5.3.1 Measured Settling Rates of Precipitates

The precipitates formed both by cooling and by combining solutions were placed in centrifuge tubes in order to determine their settling rates. After shaking each solution containing precipitate, approximately 10 ml was transferred into a centrifuge tube. The visible volume of precipitate, i.e. the volume up to where the solution appeared clear in the centrifuge tube, was then recorded at 15 min, 1 hr, 2 hr, 3 hr, and 4 hr. Table 5.3-1 presents these recorded settling rates for each precipitate formed.

As can be inferred from the settling rates presented in the table below, the precipitates formed do not settle quickly and thus cannot be discounted as a concern for sump screen performance. Note that since these are hindered settling rates, i.e., the fall of particles may be hindered due to their interaction with neighboring particles, a determination of particle size cannot be made from the data.

Table 5.3-1: Measured Settling Rates of Formed Precipitates

PPT Run	Start Volume (ml)	Volume of PPT (ml)					Average Settling Rate (mm/hr)	Note
		15 min	1 hr	2 hr	3 hr	4 hr		
1	10.2	ND	ND	ND	ND	0.01	ND	Precipitation from cooling, Al pH 4
2	10.2	10.1	9.8	9.0	8.5	7.1	9	Precipitation from cooling, Al pH 8
3	10.3	10.2	9.8	9	8.5	7.4	3	Precipitation from cooling, Al pH 12
12	10.1	ND	0.05	0.3	0.25	0.3	62	Precipitation from cooling, Other Fiberglass, pH 12
13	10.2	ND	ND	9.6	9.5	0.3	2 or 15	Precipitation from cooling, Concrete, pH 4
14	10.4	10.0	9.7	6.5/0.2	0.04	0.02	5 or 32	Precipitation from cooling, Concrete, pH 8
16	10.2	ND	ND	ND	ND	0.02	ND	Precipitation from cooling, Mineral Wool, pH 4
22	10.2	ND	ND	ND	ND	ND	ND	Precipitation from cooling, FiberFax, pH 4
24	10.2	0.3	0.6	0.7	0.7	0.7	124	Precipitation from cooling, FiberFax, pH 12
30	10.1	ND	ND	ND	0.01	0.02	ND	Precipitation from cooling, Galvanized, pH 12
35	10.3	0.4	0.3	0.3	0.3	0.3	124	PPT of Phosphates, CalSil
38	10.4	2.5	1.8	1.5	1.4	0.8	99	PPT of Phosphates, Powdered Concrete
60	9.8	9.8	0.4	0.4	0.4	0.5	59	pH 12, 265°F Fiberglass + pH 4, 190°F CalSil

5.3.2 Estimation of Precipitate Size

SEM analyses were performed on the thirteen precipitates formed during bench testing in order to estimate the size of each precipitate's constituent particles. The high magnification pictures are included in Appendix B. These pictures demonstrate that either the constituent particles are less than 20 μm or the larger agglomerated particles are approximately 20 μm , and so their constituent particles must be less than 20 μm . As can be concluded from the pictures attached in Appendix B and from literature, the types of precipitates generated from the reaction of dissolved containment materials tend to flocculate, resulting in agglomerated particles with sizes in the range of 10 to 100 μm . These particles are comprised of primary particles (floculi) of submicron size, and will likely break up under shear^{1,2}.

5.3.3 References

- 5.3-1 Biggs, C. A. and Lant, P. A., "On-Line Determination of Floc Size and the Effect of Shear," Water Research, 34(9), June 2000.
- 5.3-2 Jarvis, P., Jefferson, B. and Parsons, S., "Measuring Floc Structural Characteristics," Reviews in Environmental Science and Biotechnology. Vol 4 (1-2), May 2005.

5.4 PRECIPITATE FILTERABILITY TESTS

5.4.1 Summary

Precipitate filterability tests were carried out at the Westinghouse Science and Technology Department to determine the overall filter cake coefficients (K_f) for the various precipitates produced in the chemical effects bench testing discussed in Section 5.2. The results of these tests indicated that chemically induced precipitates produced solids with single component filter cake coefficients (K_{fx}) (average = 0.0034+/-0.0022) about half that of the Si and Al precipitates (0.0032+/-0.00202) formed on cooling. This indication comes from a relatively limited dataset and so needs to be used with care. However, the lower values could be used as an initial guess for calculating maximum pressure drops.

5.4.2 Filtration Model

The data obtained from this experiment was modelled using the following equation:

$$F = (K_{fx} / m_x) * A * dP / n \quad (\text{Equation 5-1})$$

Where:

F = total flow rate (gpm)

K_{fx} = filter cake coefficient for a specific precipitate or solid (gpm lb_m cP ft⁻⁴ psi⁻¹)

dP = measured pressure drop across filter with solids (psi or lb_f in⁻²)

n = viscosity of the liquid in the slurry (assumed to be water) (cP)

m_x = specific dry (1 hour @ 110°C) solids loading (lb_m ft⁻²)

A = flow area (ft²)

This model makes the assumption that the filter cakes are relatively thin and incompressible. This assumption was made since the applied pressure drops will be very small (on the order of 1 to 6 psi). Note that this assumption was supported by the data in that all the pressure versus flow plots obtained experimentally were reasonably linear in the low ΔP regions.

To apply this test data to calculations for screen pressure drops, the following data is required:

1. The method of bed formation, i.e., whether the bed is formed from a mix of solids or formed by layering of various solids
2. Specific dry (1 hour @ 110°C) weight of each solid ($\text{lb}_m \text{ ft}^{-2}$)
3. Either the temperature to determine the viscosity if water is assumed or the measured liquid (not slurry) viscosity
4. The K_{fs} of the screen ($\text{gpm ft}^{-2} \text{ psi}^{-1} \text{ cP}$) determined with the viscosity at the temperature of interest
5. Total flow rate (gpm) and area (ft^2)

If the bed is formed in layers, then the overall K_f can be determined analogous to the method used to determine an overall heat transfer coefficient. That is:

$$1/K_f = 1/K_{fs} + \sum m_x/K_{fx} \quad (\text{Equation 5-2})$$

Where:

K_{fs} = the screen coefficient ($\text{gpm ft}^{-2} \text{ psi}^{-1} \text{ cP}$)

m_x = specific mass of each solid (lb ft^{-2})

K_{fx} = filter cake coefficient for a specific for a specific precipitate x ($\text{gpm lb}_m \text{ cP ft}^{-4} \text{ psi}^{-1}$)

A simple mass-weighted approach may be used as a theoretical means to determine the effective K_f for a mix of solids as opposed to a single solid.

$$K_{fz} = \sum K_{fx} / m_x \quad (\text{Equation 5-3})$$

where K_{fz} is the effective K_f for the mixed solids bed.

This K_{fz} can then be used along with the screen K_{fs} in the equation below to determine the overall K_f .

$$1/K_f = 1/K_{fs} + 1/K_{fz} \quad (\text{Equation 5-4})$$

Finally, K_f can then be used to determine the pressure drop using the equation:

$$\Delta P = F / (K_f * A / n) \quad (\text{Equation 5-5})$$

5.4.3 Test Procedure

After forming precipitates in the first portion of testing described in Section 5.2, the precipitates were then tested in a filter apparatus to determine their overall filter cake coefficient using the procedure given below and the apparatus shown in Figure 1 below. The solution containing the precipitate was pumped through a filter at different flow rates in order to record the pressure drop at each flow rate. The filtration experiments were done at room temperature (between 70°F and 78°F).

Equipment List

- 4-Channel Peristaltic Pump, Pump Head Cole Parmer EW-07519-10 with cartridges Cole-Parmer EW-07519-85 and pump tubing EW-06508-14
- Pressure sensor 1- Omega PX303-0 0A10V 0-50 psia
- Pressure sensor 1- Omega PX303-050A5V 0-50 psia
- Flow sensor- McMillan Co 104 Flo-Sen S/N 1011 3
- Tubing outside pump- Cole-Parmer L/S 14 Tubing, C-96410-14
- Filter Holder-25 mm Filter Holder VWR 28144-164
- Filter – 25 mm glass fibre filter, 1-micron, 28150-134

Preparation

- Calibrate the program in order to obtain pump flow rates. Three flow rates are used in order to determine the change in pressure drop with flow rate.
- Select a 1-micron glass fibre filter and weigh it to the nearest 0.0001 g.
- Place the fibre filter in the holder.
- Measure 75 ml of 4400 ppm boron solution into settling cone.
- Place the dip tube and the return line in the settling cone.

Filtration

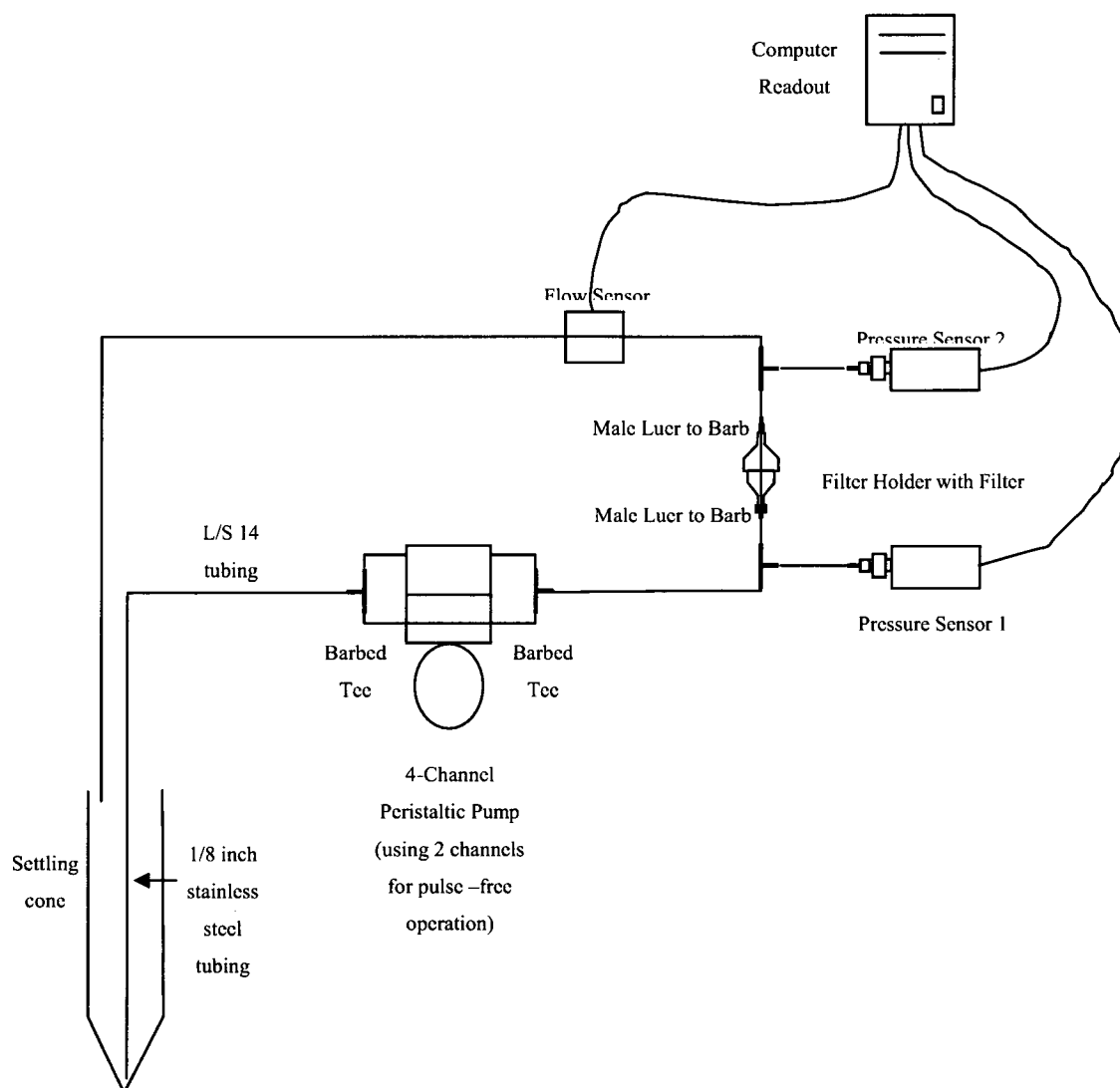
- Turn on the pump and set flow rate to the highest flow rate in order to load the filter at the beginning of the test.
- Allow sufficient time for the flow to stabilize through the filter (5 minutes). Then thoroughly shake the solution containing precipitate and add approximately 10 ml to the settling cone.
- Record pressure drop across filter with time.
- After the total solution volume has passed through the filter about four times, decrease the pump flow rate.
- Record pressure drop with time.

- After the total solution volume has passed through the filter about four times, again decrease the pump flow rate.
- Record the pressure drop with time, until approximately another 4 solution volumes have passed through the filter.

End of Experiment Tasks

- Rinse the filter with 10 ml of de-ionized water.
- Dry the filter at 110°C +/- 10°C for 1 hour.
- Weigh the filter.
- Place filter in a labelled container for later SEM analysis.
- Clean loop before next test with a flow of de-ionized water.

Figure 5.4-1 - Filter Test Equipment Schematic



The experimental data obtained were:

f = flow rate (ml/min) as a function of dP (psi)

n = water viscosity (cP) from the temperature ($^{\circ}F$)

m = dry ($110^{\circ}C$ @ 1 hour) solids (gm)

$A = 3.8 \text{ cm}^2$ measured exposed filter area

A representative figure (Figure 2 below) containing the dP versus flow rate data recorded as a function of time is presented below. Similar data is available for all of the runs conducted in order to gauge the filterability of the precipitate.

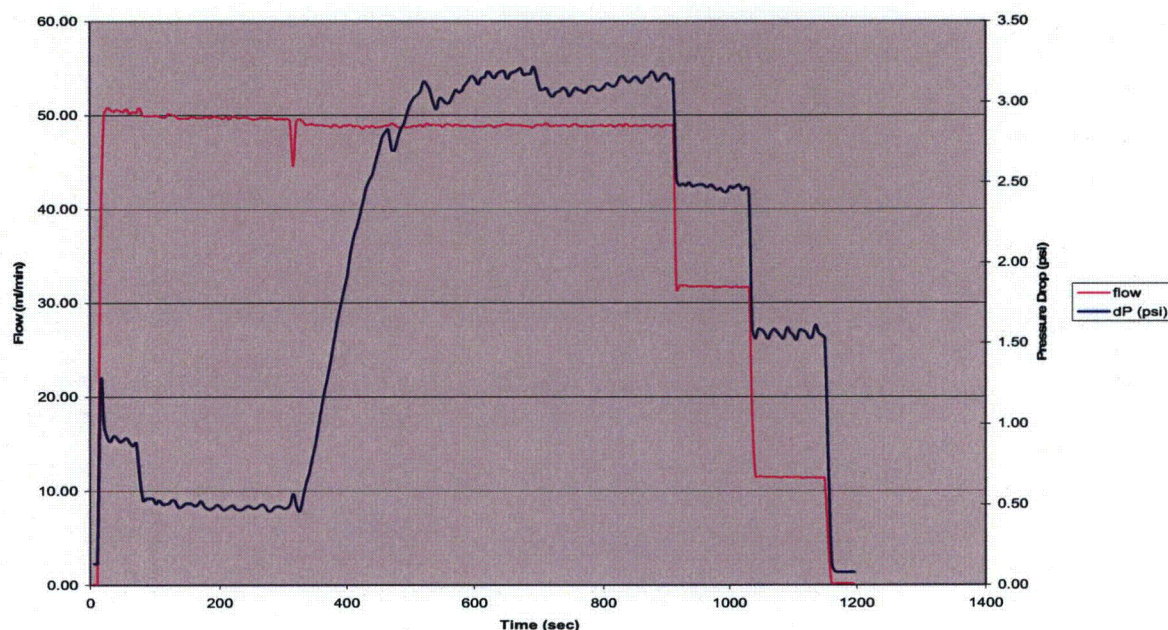


Figure 5.4-2 - dP and Flow Rate as a Function of Time for PPT 24D

Graphs of the dP versus flow rate (ml/min) are shown in Appendix C. Each set of data was analyzed in the linear portion using least squared regression analysis to obtain the slope of the curve (z in psi-min/ml). Note that some curves bent over, i.e., the flow increased with little or no increase in pressure drop. The higher flow data from these tests was not used since the upper flow data was likely taken before the solids had finished depositing on the filter. Also, some near-zero point data was not used since at very low ΔP values, there were instabilities in some of the ΔP measurements. The range of data that was used from each test is indicated on the data plots given in Appendix C. This slope was then combined with the water viscosity, solids weight and effective filter area to determine the overall (filter + cake) K_f using the equation:

$$K_f = n / A / z / [3785 \text{ ml/gal}] \quad (\text{Equation 5-6})$$

The K_{fs} (filter cake coefficient) for a specific precipitate was obtained from the slope (z) of the dP versus flow measurement for the filter (Figure C-1) using the equation:

$$K_{fs} = n / A / z / [3785 \text{ ml/gal}] \quad (\text{Equation 5-7})$$

Note that by using the slope, it was assumed that the pressure versus flow data passed through the point 0,0. The K_{fx} (filter cake coefficient for a specific precipitate ($\text{gpm lb}_m \text{ cP ft}^{-4} \text{ psi}^{-1}$)) was then obtained by substituting Equation 5-7 into Equation 5-2 and solving the resulting equation for K_{fx} :

$$m / A / K_{fx} / [454 \text{ gm/lb}] = 1/K_f - 1/K_{fs} \quad (\text{Equation 5-8})$$

Note that the K_{fs} was corrected to the viscosity at the temperature at which each filtration test was run.

5.4.4 Results

The results from these tests are summarized in Table 1 below. The dP versus flow data is presented for each run in Appendix C. These results indicate that the K_{fx} for the various precipitates range from 0.0001 to 0.0066 after discounting results from those PPT tests that had too little precipitate to result in a discernible dP measurement: PPT runs 1, 13, 14, 16, 22 and 30.

For PPT runs 1, 14, and 16, the dP vs. flow data indicate that the head loss with debris laden filters is comparable to or less than the clean filter head loss. This anomaly may be attributed to either some bypass of the filter or slight errors in the pressure measurements which could cause a negative number when the difference of two small numbers is determined.

The remaining PPT runs are listed below.

Table 5.4-1: Precipitate Filter Coefficients

PPT Run	Precipitation Formation Method	Individual Filter Cake Coefficients (K_{fx})	Overall Filter Cake Coefficients (K_f)
2	PPT on cooling, Al pH 8	0.0033	0.15
3a	PPT on cooling, Al pH 12	0.0008	0.93
12	PPT on cooling, Other Fiberglass, pH 12	0.0009	1.15
24a	PPT on cooling, FiberFax, pH 12	0.0066	1.81
24b	PPT on cooling, FiberFax, pH 12	0.0043	1.30
24c	PPT on cooling, FiberFax, pH 12	0.0027	0.88
24d	PPT on cooling, FiberFax, pH 12	0.0039	1.19
35	PPT of Phosphates, CalSil	0.0033	1.93
38	PPT of Phosphates, Powdered Concrete	0.0001	0.05
60	pH 12, 265 Fiberglass (high sulfur), with high calcium from pH 4 CalSil.	0.0017	1.87

This data indicates that:

1. Phosphates cause precipitation by super saturation at temperature and have low individual filter cake constants (K_{fx}) (average = 0.0034 +/- 0.0022). The other precipitate, PPT 60, has a similar value of K_{fx} (0.0017). The large uncertainty of the results is due to the limited number of phosphate precipitation runs for which filtration filter coefficients may be developed.
2. The Si and Al precipitates formed on cooling have relatively high individual cake coefficients (K_{fx}) (0.008 to 0.0066, average = 0.00321 +/- 0.00202).
3. The repeated PPT24 runs had an average K_{fx} of 0.00438 +/- 0.00163 with a range of 0.0027 to 0.0066. This is about the same as the entire set of data (average = 0.00276 +/- 0.00196).

6.0 CHEMICAL MODEL

6.1 INTRODUCTION

The results of this test program, consistent with previous work such as the ICET program, show that the predominant chemical precipitates are aluminum oxyhydroxide, sodium aluminum silicate and calcium phosphate (for plants using trisodium phosphate for pH control). Other minor silicate materials may also be generated (e.g., calcium aluminum silicate or zinc silicate), but the contribution of these materials is expected to be small relative to the predominant precipitates (i.e., less than 5 percent). On this basis, the chemical model considers only the release rates of aluminum, calcium and silicate. Other chemical species may be ignored. A more detailed justification for eliminating zinc and iron materials is included in Sections 6.2.2 and 6.2.3, respectively. The reason for not considering nickel and copper based materials is given in Section 5.1.2, "Containment Materials".

The primary source of aluminum is from corrosion of aluminum alloys present in coatings, structural members and in components such as valves and instrument blocks. A minor aluminum contribution results from dissolution of aluminum silicate and other aluminum bearing minerals in insulation (e.g., Durablanket or mineral wool) and concrete. The release rate of aluminum from aluminum alloys is fairly constant over time for a given set of chemistry and temperature conditions. The release rate of aluminum from these materials decreases with time as the applicable solubility limit is approached. Additionally, the release rate from aluminum silicate insulation materials decreases with increasing concentration of dissolved aluminum from all sources due to the common ion effect. It should be noted that aluminum corrosion is not affected by the mode of solution exposure¹, so there is no need to develop different modeling equations for aluminum that is submerged in the sump pool and for aluminum exposed only to the containment spray solution.

The primary sources of calcium are concrete and calcium silicate insulation. Minor contributors include fiberglass and mineral wools. As with aluminum from aluminum-bearing minerals, the release rate of calcium from these materials decreases with time as the solubility limit is approached.

It should be noted that silicate is recognized as an effective inhibitor for corrosion of aluminum alloys². This effect was observed during selected testing performed as part of the ICET program. Evaluation of this effect was not performed as part of this single-effect test program, and is therefore not explicitly included in the current model. This adds some degree of conservatism to the model. The exact degree of conservatism is a function of the conditions under which the bulk of the aluminum release occurs. For example, aluminum release from non-submerged aluminum would not be affected, nor would aluminum release that occurs prior to significant release of silicate.

6.1.1 References

- 6.1-1 J. C. Griess and A. L. Bacarello, "Design considerations of Reactor Containment Spray Systems- Part III. The Corrosion of Materials in Spray Solutions," Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.
- 6.1-2 Revie, R. Winston, ed. Uhlig's Corrosion Handbook (2nd Edition). John Wiley & Sons, 2000.

6.2 DETERMINATION OF RELEASE RATE EQUATIONS

For each chemical species, concentration data generated during bench testing at specific chemistry conditions were used in a regression analysis to develop release rate equations as a function of temperature, pH, and the concentration of that species. Equations were developed for each predominant source material for each chemical species. For example, different functions were used to calculate calcium release from calcium silicate and concrete.

6.2.1 Metallic Aluminum

The release rate data for aluminum metal was much different from that of the insulation materials. The release rate increases dramatically as the pH was increased above 8 and release rates were especially high at 265°F. The fitting function that was used to describe the aluminum release is shown in Equation 6-1:

$$RR=10[A + B(pHa) + C(1000/T) + D(pHa)^2+E(pHa)(T)/1000] \quad \text{Equation 6-1}$$

where:

RR = release rate in mg/(m² min)

A = -4.049

B = -0.4371

C = 0.7172

D = -0.024398

E = 3.065

pHa = initial pH corrected to 25°C

T = temperature (°K)

This equation was developed by using multiple linear regression to fit experimental log(RR) values. The form of the equation was selected empirically by fitting several different equations to the data and comparing the goodness of fit. A good fit to the experimental data was obtained for Equation 6-1 with all terms being significant ($p < 0.05$) except for B ($p = 0.13$). The fit of the model to the experimental data is shown in Figure 6.2-1.

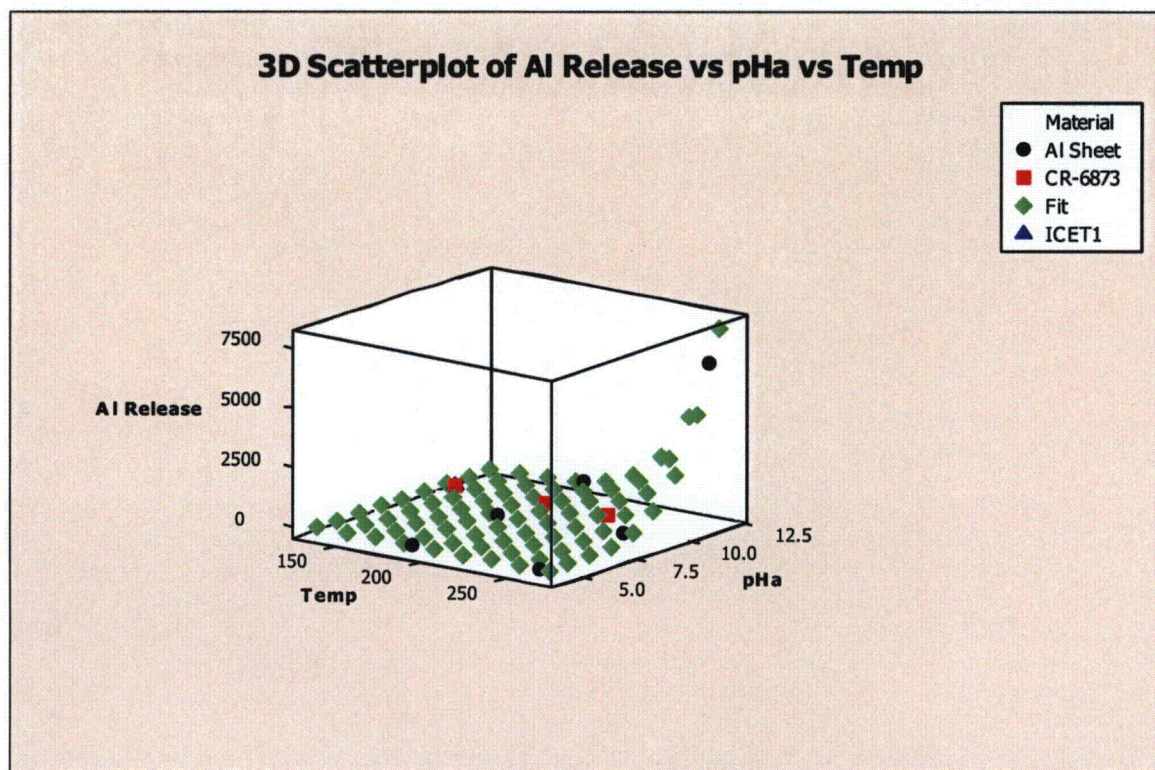


Figure 6.2-1: Predicted Al Release Using Equation 6-1 Compared to Experimental Data from the Program (Al Sheet) and Reference Data (Temperature in Units of °F).

There was some initial concern that the corrosion rates measured for aluminum in this work were erroneously high and that the model predicted excessive corrosion releases. The release rates predicted using Equation 6-1 were about ten times higher than the actual release rate measured in ICET Test 1¹ and those measured by Jain et. al.²

Because of the concern that the aluminum release rates were too high, several longer dissolution tests were done at intermediate pH values. Also, additional literature data was obtained from Oak Ridge³. The Oak Ridge data for aluminum Alloy 1100 corrosion was consistent with that obtained in the dissolution testing. Furthermore, the longer-term release data (1 day) measured at 190°F and pH 9.4 and 10.0 were consistent with that obtained in the dissolution tests. The results of the bench scale dissolution tests, the longer-term tests, and the Oak Ridge data are compared in Figure 6.2-2. There was no indication that the release rate changed significantly from 90 min to 4 hours to 20 hours since the corrosion rates calculated for these time periods were very similar. Therefore, it is reasonable to conclude that the bench test dissolution rates and Equation 6-1 are accurate.

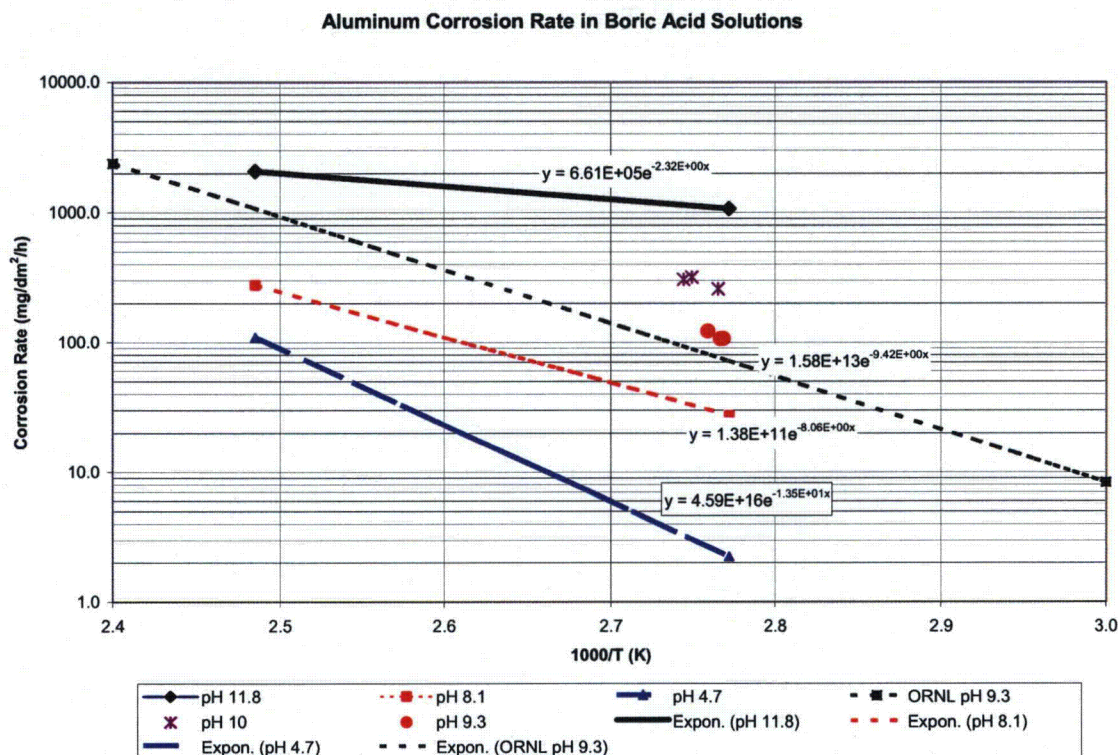


Figure 6.2-2: Corrosion Release for Aluminum Alloy 1100: Bench Test Data Compared to Oak Ridge Data

Aluminum corrosion data from WCAP-7153A⁴ is often used in safety analyses concerned with post-LOCA containment hydrogen generation, so this data was also compared to the bench test data. The corrosion rates in WCAP-7153A had greater pH dependence than the bench test corrosion rates with the WCAP-7153A data bracketing the bench test data.

The aluminum model was refined by inclusion of literature data within the data set and repeating the fitting process. This was done primarily to improve model predictions at temperatures below the range covered by the bench scale testing. The literature data included in the model is shown below in Table 6.2-1. Equation 6-2 gives the results of the fit.

Table 6.2-1: Data Used in Aluminum Corrosion Model

Source	Label	Temperature (°F)	pH	Corr. Rate/Area (mg/m ² -min)
Bench Test	Al Sheet	190	4.1	9.29
Bench Test	Al Sheet	190	8	44.7
Bench Test	Al Sheet	190	12	1001
Bench Test	Al Sheet	265	4.1	89.4
Bench Test	Al Sheet	265	8	395
Bench Test	Al Sheet	265	12	3338
Oak Ridge A1100 Runs (2)	CR-6873	140	10	16.4
Oak Ridge A1100 Runs (2)	CR-6873	194	10	31.5
Oak Ridge A1100 Runs (2)	CR-6873	230	10	36.7
ICET 1 Average (1)	ICET1	140	10	12.2
WCAP 7153A A1100 Runs (3)	Al coupon	210	7	1.30
WCAP 7153A A1100 Runs (3)	Al coupon	210	8	12.2
WCAP 7153A A1100 Runs (3)	Al coupon	210	9	216
WCAP 7153A A1100 Runs (3)	Al coupon	210	10	6076

$$RR=10[A + C(1000/T) + D(pHa)^2 + E(pHa)(T)/1000] \quad \text{Equation 6-2}$$

where: RR = release rate in mg/(m² min)

$$A = 14.69039$$

$$C = -4.64537$$

$$D = 0.044554$$

$$E = -1.20131$$

pHa = initial pH corrected to 25°C

T = temperature (°K)

The fit to the combined data set was much poorer than the fit to the bench test aluminum data alone as would be expected since the materials and methods used to determine the corrosion rates varied from laboratory to laboratory. The multiple R-squared value was 0.77. The p-value for the “A” coefficient was 0.05, and the values for C, D, and E were 0.04, 0.20 and 0.40, respectively. The “B” coefficient from the linear pHa term, was dropped since its inclusion decreased the adjusted R-squared obtained for the regression.

The fit of the data to the predictions of Equation 6-2 are shown in Figure 6.2-3. The predicted values are displayed on a log scale. It is clear that the WCAP-7153A data labeled “Al coupon” shows a stronger pH dependence than the corrosion data from other sources. The other corrosion data all appears to be part of the same population and was fit reasonably well with Equation 6-2.

At intermediate times (i.e., less than 30 days), Equation 6-2 will underpredict the release rate. Hence, the cumulative 30-day integrated aluminum product release predicted by this equation should be used for screen testing, even if an intermediate time period is being simulated. If a cumulative value at an intermediate time is desired, individual plants must justify the derivation of that value.

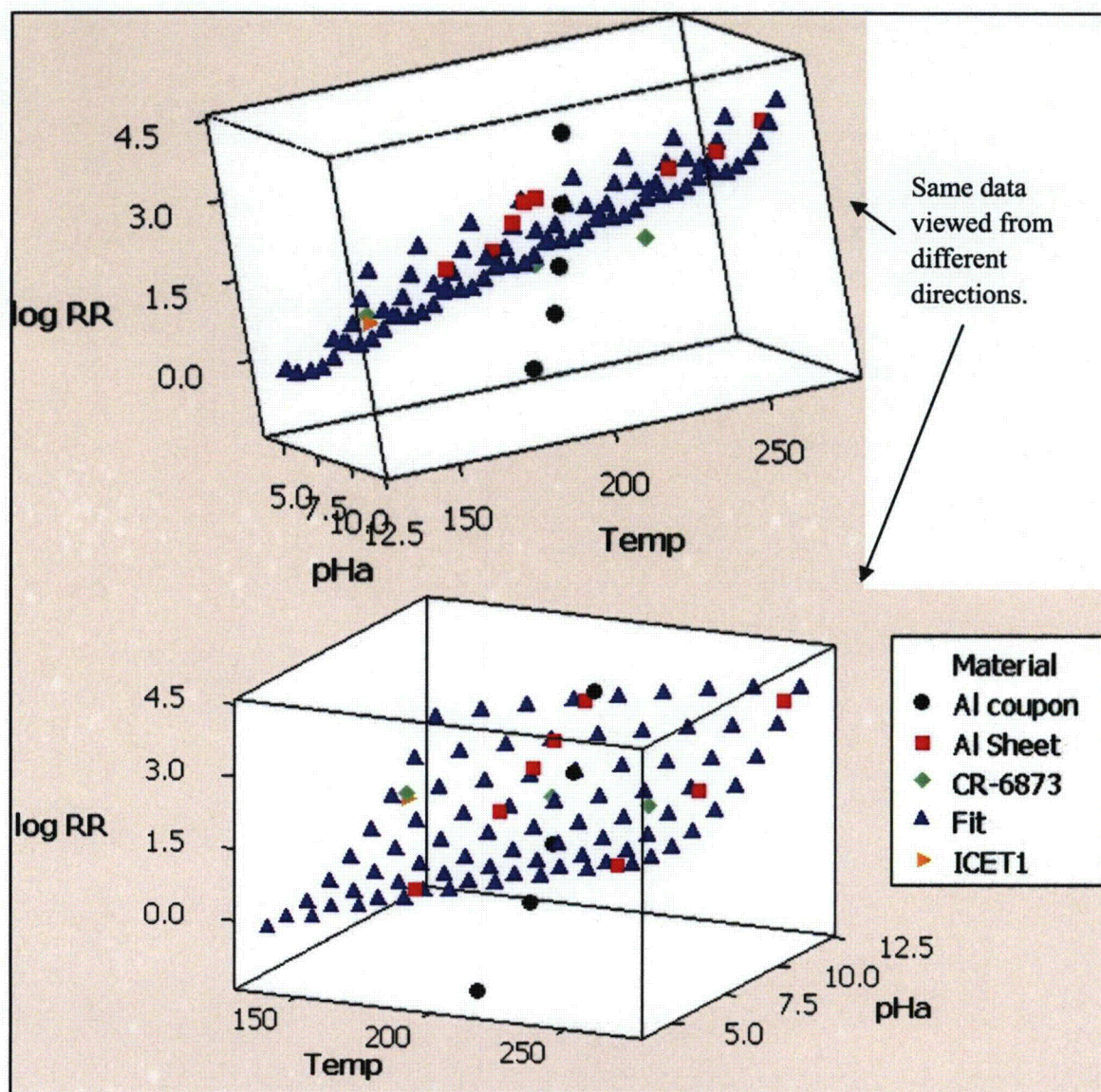


Figure 6.2-3: Fit of Equation 6-2 to Experimental Aluminum Alloy 1100 Corrosion Data

It is suggested that Equation 6-2 be used in chemical effects modeling since it was developed using a wider range of input data than Equation 6-1.

6.1.1 Galvanized Steel

A function was fit to the bench test zinc release rate data so the corrosion of galvanized steel material and other materials containing metallic zinc could be modeled. The form of the equation was the same as for the aluminum model.

$$RR=10[A + B(pHa) + C(1000/T)+ D(pHa)^2+E(pHa)(T)/1000]$$

Equation 6-3

where:

RR = release rate in $\text{mg}/(\text{m}^2 \text{ min})$

A = -15.10693334

B = -3.670953896

C = 7.303961651

D = 0.103589245

E = 5.485050709

pHa = initial pH corrected to 25°C

T = temperature (°K)

The zinc release rates were predicted at 10 different PWRs using utility supplied pH-time curves and either utility-supplied or generic containment temperature profiles. The plants had a variety of pH control agents. The exposed zinc surface areas were as high as 325,215 square feet. It was assumed un-submerged material did not contribute to zinc releases after termination of the spray phase. The integrated zinc mass releases are given in Table 6..

Table 6.2-2: Predicted Integrated Zinc Release for 30 Days Post-LOCA

Plant Code	Buffer	Zn Release from Unsubmerged Material (kg)	Zn Released from Submerged Material (kg)
G	TSP	0.646	3.29
C	Borax	0.168	6.115
F	TSP	0.258	3.991
E	NaOH	0.019	0.263
D	NaOH	0.578	0.304
A	TSP	0.134	3.711
J	Borax	0.855	0.136
I	NaOH	0.047	0.191
B	TSP	0.006	3.824
H	NaOH	0.07	0.758

The zinc releases were relatively small and can be ignored in chemical effects precipitation modeling.

6.2.3 Uncoated Steel

The release rates for iron from uncoated steel in the bench tests were on the same order as the zinc release rates, so iron can also be ignored in chemical effects precipitation modeling.

6.2.4 Silicates

All of the insulation materials contain silicates as major components. It has been shown³ that the release rate of silica from a wide range of silicate glasses can be modeling using Equation 6-4:

$$RR = kA(1-C/K) \quad \text{Equation 6-4}$$

where:

RR = release rate

A = amount of material (typically described in terms of area but mass was used in this work)

k = a constant dependent on pH and temperature

C = the concentration of the released species

K = the saturation limit of the released specie (a quasi-equilibrium constant)

This equation was used to model the release calcium and aluminum from the insulation materials as well as silicon. The steps used to develop the model follow:

1. Values of K and k were estimated for each run (e.g. K and k were estimated for the release of calcium from CalSil at 190°F and pH 4.1). A non-linear regression using Marquardt's algorithm was for estimation.
2. The various K and k values from different pHs and temperatures were all collected for the release of a given species from a material (e.g. The six k and six K values for Ca release from CalSil were considered together)
3. An equation was fit to each K and k value to model the temperature and pH variation of these parameters.

The form of each equation used to model the temperature and pH dependence of K is given in Equation 6-5:

$$K=10[a + b(pH_a) + c(1000/T)] \quad \text{Equation 6-5}$$

where:

a, b, and c are the fitted constants and T = temperature (°K)

likewise, Equation 6-6 was used to fit the rate constant k:

$$k=10[d + e(pH_a) + f(1000/T)] \quad \text{Equation 6-6}$$

Thus, six constants and three equations were used to predict the rate of release of a given species from a material as a function of pH, temperature and concentration of that species.

The modeling constants for different insulation materials are given in Table 6.2-3.

Table 6.2-3: Constants for Release Rate Prediction

Class	Released Material	Saturation Constant "K"			Rate Constant "k"		
		a	b	c	d	e	f
Calcium Silicate	Ca	-2.4063	-0.17595	1.967023	-2.35331	-0.15044	1.820687
Calcium Silicate	Si	0.12735	0.03197	0.71658	7.55470	-0.04084	-2.02198
Concrete	Ca	-0.15969	-0.04542	0.95477	5.31705	-0.07459	-1.10803
Concrete	Al	2.35338	0.06829	-0.70953	9.23778	0.05404	-3.34577
Concrete	Si	1.05597	0.01483	0.11862	3.50061	-0.01713	-0.74261
E-Glass	Ca	1.82949	0.06821	-0.47088	3.67611	0.02616	-0.96191
E-Glass	Si	5.20122	0.10404	-1.50553	7.46511	0.16247	-2.55813
E-Glass	Al	3.72351	0.14041	-1.69396	10.35371	0.17064	-4.17804
Min-K	Si	1.17043	0.10511	-0.07315	7.41106	0.17893	-1.93332
Aluminum Silicate	Al	5.52900	0.24010	-2.51326	8.48062	0.20749	-3.32039
Aluminum Silicate	Si	7.51336	0.18619	-2.89181	7.17588	0.11502	-2.42532
Mineral Wool	Ca	2.30159	0.12022	-0.82549	1.98549	0.09009	-0.52443
Mineral Wool	Al	8.96613	0.10871	-2.37200	6.62900	0.13222	-2.57256
Mineral Wool	Si	5.95046	0.06796	-1.43151	6.07665	0.16569	-2.17413
Interam	Si	13.60515	0.18354	-3.81145	15.69692	0.34838	-6.05941

The multiple R value is given in Table 6.2-4 for each of the linear regressions. The multiple R value is a measure of correlation with a value of "1" indicating a perfect prediction of k or K from the pH, T, and concentration data.

Table 6.2-4: Multiple R Values

Class	Released Material	Prediction of log(K)	Prediction of log(k)
Calcium Silicate	Ca	0.93	0.71
Calcium Silicate	Si	0.83	0.85
Concrete	Ca	0.78	0.94
Concrete	Al	0.43	0.37
Concrete	Si	0.52	0.50
E-Glass	Ca	0.66	0.95
E-Glass	Si	0.80	0.84
E-Glass	Al	0.67	0.88
Min-K	Si	0.91	0.89
Aluminum Silicate	Al	0.91	0.89
Aluminum Silicate	Si	0.98	0.83
Mineral Wool	Ca	0.99	0.60
Mineral Wool	Al	0.94	0.95
Mineral Wool	Si	0.88	0.99
Interam	Si	0.74	0.69

6.2.5 Model Verification

Aluminum and CalSil are anticipated to contribute heavily to precipitation in many plants so model predictions for releases from these materials were verified by comparing the predictions to those obtained experimentally in other laboratories or to predictions made by other verified software.

The chemical effects dissolution model was verified for aluminum dissolution by comparing the aluminum corrosion predictions to those obtained with the computer code GENNY⁶. The GENNY computer program calculates hydrogen produced from aluminum corrosion in a post-LOCA environment. The chemical effects aluminum release data can be converted to hydrogen release using Equation 6.7 below:



Post-LOCA aluminum corrosion was estimated for the time-temperature-pH evolution using GENNY and also with the chemical effects model. Good agreement was obtained. The chemical effects model predicted an average hydrogen generation rate of 36.1 standard cubic feet per minute over the first three hours of the accident, while GENNY predicted 39.3.

Table 6.2-5: Containment Temperature and Coolant pH Timelines used in Verification of Aluminum Release Rate Predictions

Start of Interval (hrs)	End of Interval (hrs)	Average Interval pH	Average T (°F)
0.0000	0.0001	10.5	140.0
0.0001	0.0003	10.5	160.0
0.0003	0.0006	10.5	180.0
0.0006	0.0008	10.5	202.5
0.0008	0.0017	10.5	222.5
0.0017	0.0028	10.5	240.0
0.0028	0.0056	10.5	257.5
0.0056	0.0278	10.5	270.0
0.0278	0.1111	10.5	272.5
0.1111	0.3472	10.5	267.5
0.3472	1.0000	10.5	247.5
1.0000	1.3889	10.5	182.5
1.3889	2.0000	10.0	142.5
2.0000	3.0000	9.5	148.5

The predictions for the dissolution of CalSil were verified by predicting calcium release in ANL CalSil dissolution tests⁸ and comparing the predictions to the actual measured calcium levels. The results are shown in Table 6.3-1. The trend of increasing dissolution with decreasing pH was predicted by the model. The saturation of solutions was also predicted. However, the chemical effects model over-predicted the calcium concentrations for dissolution experiments performed at pH 4.5, 7, and 10.1 for all but one of the measurements. The chemical effects model under-predicted the rate of CalSil release for the pH 4 runs, but over-predicted the

apparent saturation level. The moderate over-prediction of saturation values occurred because data was taken at intervals that were too long to capture the rapid initial dissolution of CalSil.

Overall, the model performance for calcium silicate dissolution appears to be conservatively high but reasonable, especially given the variability in the experimental values.

Statistical estimation of the confidence interval for each parameter in Table 6.2-3 was performed. Typically, the confidence intervals were quite large ($\pm 100\%$ of parameter value) due to the small numbers of samples used in the fitting process. More replicates are necessary to evaluate the model errors statistically.

Table 6.2-6: Prediction of Calcium Levels in Argonne CalSil Dissolution Tests

Test	Starting pH	T (C)	Time	CalSil Added (g/l)	Measured Ca (ppm)	Model Prediction (ppm)
1	4	60	35	6	176	48
2	4	60	35	15	256	114
3	4	60	35	25	244	181
4	4	60	35	166	228	588
5	4	60	240	6	196	307
6	4	60	240	15	195	521
7	4	60	240	25	195	600
8	4	60	240	166	168	624
9	4.5	60	240	6	156	256
10	4.5	60	240	15	169	430
11	4.5	60	240	25	184	492
12	4.5	60	240	166	127	509
13	7	62	240	2	45	40
14	7	62	240	6	88	95
15	7	62	240	25	69	167
16	7	62	1440	2	73	140
17	7	62	1440	6	108	170
18	7	62	1440	25	102	170
19	10.1	60	210	6	17	30
20	10.1	60	210	15	18	47
21	10.1	60	210	25	20	52
22	10.1	60	210	166	23	53

6.2.4 References

- 6.2-1 LA-UR-05-0124, Integrated Chemical Effects Test Project: Test #1 Data Report, June 2005.
- 6.2-2 V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.

- 6.2-3 J. C. Griess and A. L. Bacarello, "Design considerations of Reactor Containment Spray Systems- Part III. The Corrosion of Materials in Spray Solutions," Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.
- 6.2-4 M. J. Bell, J. E. Bulkowski, L. F. Picone, "Investigation of Chemical Additives for Reactor Containment Sprays" WCAP-7153A, April, 1975.
- 6.2-5 William L. Bourcier, "Critical Review of Glass Performance Modeling", Argonne National Laboratory Report ANL-94/17, July 1994.
- 6.2-6 James Sejvar, "Release of GENNY 5.2", SAE-REA-00-586, March 2000.
- 6.2-7 D. M. Chapman, "Surry 1 & 2 Mini-Uprate Post-LOCA Hydrogen Generation Analysis, CN-REA-02-47, June, 2002, Westinghouse Electric Company.
- 6.2-8 J. Oras, J. H. Park, K. Kasza, K. Nalesan, W. J. Shack, "Chemical Effects/Head Loss Testing Quick Look Report, Tests 1&2, September 16, 2005.

6.3 USE OF RELEASE RATE EQUATIONS TO DETERMINE RELEASES AND CONCENTRATIONS

The initial step in determination of release rates is to define the quantity of starting materials that will be exposed to the coolant. The amount of coolant in the ECCS should be determined using the average mass during the LOCA being modeled. The amount of each material in containment should be defined and assigned to the appropriate class per the class assignments in Section 3.2. The total quantity of material in each class should then be calculated.

The quantities of each material should be converted to the units used in this model. The units to be used are shown in Table 6.3-1 along with the units for release.

Table 6.3-1: Units for Chemical Model

Material	Material Units	Release Units
Aluminum	m ²	mg/m ² -min
Calcium Silicate	kg	mg/kg-min
Concrete	kg	mg/kg-min
E-glass	kg	mg/kg-min
Min-K	kg	mg/kg-min
Aluminum Silicate	kg	mg/kg-min
Mineral Wool	kg	mg/kg-min
Interam	kg	mg/kg-min

Density values are needed to convert insulation volume to mass and such density values should be material specific. For all materials other than concrete, the "as-fabricated" density values given in Table 3-2 of NEI 04-07 (Reference 6.3-1) or density values dictated by plant requirements should be used. Concrete is typically described in terms of uncoated surface area, and this should be converted to an equivalent number of kilograms of pulverized concrete using

the conversion factor of $1.0058\text{E-}5 \text{ kg/ft}^2$. This conversion factor is determined from the specific surface area for concrete given in Section 5.1.2.1 to be $9.24 \text{ m}^2/\text{g}$.

$$\text{Concrete conversion factor} = (1 / 9.24 \text{ m}^2/\text{g}) / 10.76 \text{ ft}^2/\text{m}^2 / 1000 \text{ g/kg} = 1.0058\text{E-}5 \text{ kg/ft}^2$$

The next step is development of a temperature and pH profile for the loss of coolant transient. These data will be used as inputs in a numeric integration of the release rate equations to determine the release of a species over time as well as the dissolved concentration of the species over time. A separate pH and temperature profile should be used for the spray.

The next step is the numerical integration of the release over a suitable interval. The integration interval should be short enough to capture information on rapidly changing temperatures and pH values. Typically, the integration period should be near one minute early in the LOCA. For each time interval and each species, use the containment material class mass, the interval pH and the interval temperature to predict the release rate using Equations 6-2 and 6-4 through 6-6. The concentration of each species at the start of the interval in units of ppm is also required for the prediction. Assume that the concentration is zero for all species at time zero, the start of the LOCA. The release rate is multiplied times the interval length to calculate the mass release. The mass release in mg is added to the integral mass, and the total mass is divided by the coolant mass in kg to get the new species concentration. The total mass released into the coolant should be limited by the initial mass if this quantity is known.

6.3.1 Reference

- 6.3-1 NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

6.4 DETERMINATION OF THE QUANTITY OF PRECIPITATES GENERATED

Due to the limited solubility of the key chemical precipitates, it may be conservatively assumed that essentially all of the dissolved aluminum will form precipitates upon cooling. Because the solubility of calcium silicate increases at lower temperatures (constant pH conditions) dissolved calcium will remain in solution in the absence of phosphate. Thus, the types of precipitates generated will be dependant on plant sump chemistry as well as sump materials.

Based on the chemistry of the key precipitates formed from predominant dissolved species, it is judged that the quantity and morphology of the precipitates would not be fundamentally affected by changes in temperature (predominantly cooling) during precipitate formation. Specifically, the precipitates generated are amorphous and demonstrate qualitatively slow settling behavior and qualitatively poor filterability. It is not expected that temperature changes would fundamentally alter these characteristics with respect to their effect on sump screen performance. Additionally, based on the very low solubility of the key precipitates, the model assumes that 100 percent of the aluminum and calcium (in the presence of phosphate) form precipitates. This conservative assumption effectively eliminates any influence temperature variations during precipitate formation may have on the ultimate quantity of precipitates formed.

To determine the quantity of the key precipitates, the quantity of the elements that make up the precipitates must be determined using the chemical model. It is assumed that sodium (Na), hydroxyl (OH⁻), and phosphate (if applicable) will be present in excess. Using the stoichiometry of the precipitates, the quantities may be calculated directly. The formulas for the three key precipitates are provided below. Note, for the case of sodium aluminum silicate, it is first necessary to determine whether aluminum or silicon is the limiting component. An example of generation of the calcium phosphate formula is also provided below.

Plants Using Either Sodium Hydroxide or Sodium Tetraborate Buffers

Based on thermodynamic calculations previously reported¹, dissolved aluminum, sodium and silicate will precipitate as sodium aluminum silicate (NaAlSi₃O₈). It is expected that the quantity of sodium aluminum silicate generated will be limited by the amount of available silicate. This will be the case if the concentration of silicate is less than 3.11 times the concentration of aluminum. All aluminum that does not precipitate as sodium aluminum silicate will precipitate as aluminum oxyhydroxide (AlOOH).

Thus, the quantity of precipitate generated may be calculated as:

$$\text{If } [\text{Si}] > 3.12 * [\text{Al}] : \text{NaAlSi}_3\text{O}_8 = [\text{Si}] * 3.11$$

$$\text{If } [\text{Si}] < 3.12 * [\text{Al}] : \text{NaAlSi}_3\text{O}_8 = [\text{Al}] * 9.72$$

$$\text{AlOOH} = \{ [\text{Al}] - 0.32 * [\text{Si}] \} * 2.22$$

Plants using Trisodium Phosphate Buffer

For plants using trisodium phosphate, calcium phosphate with an assumed chemical form of Ca₃(PO₄)₂ will also be generated in addition to sodium aluminum silicate and aluminum oxyhydroxide as discussed above. Note, the presence of silicate would be expected to inhibit the release of aluminum due to corrosion of metallic aluminum; however, this factor is not considered in this model. The quantity of calcium phosphate generated may be calculated as:

$$\text{Ca}_3(\text{PO}_4)_2 \text{ molecular weight: } 310.18 \text{ g-atom/mole}$$

$$\text{Ca molecular weight: } 40.08 \text{ g-atom/mole}$$

$$\text{Ca to Ca}_3(\text{PO}_4)_2 \text{ conversion factor: } \text{Ca}_3(\text{PO}_4)_2 \text{ molecular weight} / 3 * \text{Ca molecular weight}$$

where the factor of three accounts for the fact that there are three calcium atoms per atom of calcium phosphate.

$$\text{Ca}_3(\text{PO}_4)_2 = [\text{Ca}] * 2.58$$

6.4.1 Reference

- 6.4-1 V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.

6.5 SENSITIVITY STUDY

6.5.1 Base Case

The performance of the model was investigated using the spreadsheet implementation described in Section 8.2 along with containment data from the GSI-191 Containment Materials Survey. The model was first used to predict the precipitate formation at a CalSil plant with the input parameters set at levels expected from a large break LOCA. After the "base run" some of the key inputs were then varied and changes in the predicted precipitation were recorded and evaluated.

The containment materials in the base run are given in Table 6.5-1. The plant that was simulated had a fairly simple mix of materials as was not unusual for a CalSil plant. The aluminum area was near the center of the range of survey responses and, as was typical from the plant surveys, most of the aluminum was not submerged. The exact mass of aluminum was not known for this plant, so a conservative large number (1,000,000 lbm) was entered for both the mass of submerged and un-submerged aluminum. The break analysis predicted that 97 cubic feet of CalSil would be dislodged and transported into the sump. The fiberglass transported to the sump was 1180 cubic feet, a value toward the center of the fibrous insulation distribution among the surveyed plants. While the containment had a large area of exposed concrete, none was predicted to be submerged or transported to the sump.

Table 6.5-1: Materials Input for Chemical Model

Class	Material	Amount
Coolant	Sump Pool Volume (ft3)	55,169
Metallic Aluminum	Aluminum Submerged (sq ft)	1575
	Aluminum Submerged (lbm)	1000000
	Aluminum Not-Submerged (sq ft)	155925
	Aluminum Not-Submerged (lbm)	1000000
Calcium Silicate	CalSil Insulation(ft3)	97
	Asbestos Insulation (ft3)	0
	Kaylo Insulation (ft3)	
	Unibestos Insulation (ft3)	
E-glass	Fiberglass Insulation (ft3)	1180
	NUKON (ft3)	
	Temp-Mat (ft3)	
	Thermal Wrap (ft3)	
Silica Powder	Microtherm (ft3)	0
	Min-K (ft3)	0
Mineral Wool	Min-Wool (ft3)	0
	Rock Wool (ft3)	
Aluminum Silicate	Cerablanket (ft3)	
	FiberFrax Durablanket (ft3)	0
	Kaowool (ft3)	
	Mat-Ceramic (ft3)	
	Mineral Fiber (ft3)	
	PAROC Mineral Wool (ft3)	
Concrete	Concrete (ft2)	0
Trisodium Phosphate	Trisodium Phosphate?	1
Interam	Interam (ft3)	0

The default density values used for the containment materials are collected in Table 6.5-2.

Table 6.5-2: Density Values Used in Model and Calculated Masses

Class	Material	Amount	Density (lb/ft3)	Mass(kg)
Coolant	Sump Pool Volume (ft3)	55169	60.957	1525418.1
Metallic Aluminum	Aluminum Submerged (sq ft)	1575.00		0.0
	Aluminum Submerged (lbm)	1000000		45359.7
	Aluminum Not-Submerged (sq ft)	155925		0.0
	Aluminum Not-Submerged (lbm)	1000000		45359.7
Calcium Silicate	CalSil Insulation(ft3)	97	14.15	622.6
E-glass	Fiberglass Insulation (ft3)	1180	4	2141.0

The pH and temperature timelines are shown in Table 6.5-3. Only the sump pH values were provided by the plant. The spray pH values were at first assumed to be at the pH of the RWST, and then after the start of recirculation, the pH of the spray was assumed to be the same as the sump. The temperatures of the sump and containment atmosphere were not provided by the plant

but instead were engineering estimates selected for the purpose of this exercise. It was assumed that recirculation started after 30 minutes.

Table 6.5-3: Variation of pH and Temperature with Time after LOCA-Base Case

Time (sec)	(min)	(hr)	(day)s	Sump pH	Sump Temp. (°F)	Sump Mixed 1=Yes	Spray pH	Containment Temp. (°F)
6	0	0	0	5.6	212	0	4.4	222
30	1	0	0	5.6	222	0	4.4	232
60	1	0	0	5.6	212	0	4.4	222
120	2	0	0	5.6	213	0	4.4	223
180	3	0	0	5.6	214	0	4.4	224
200	3	0	0	5.6	214	0	4.4	224
400	7	0	0	6.7	220	0	4.4	230
600	10	0	0	7.2	224	0	4.4	234
800	13	0	0	7.4	229	0	4.4	239
1000	17	0	0	7.5	230	0	4.4	240
1200	20	0	0	7.5	230	0	4.4	240
1400	23	0	0	7.5	222	0	4.4	232
1600	27	0	0	7.5	211	0	4.4	221
1800	30	1	0	7.5	200	0	4.4	210
3200	53	1	0	7.5	187	0	7.5	197
4600	77	1	0	7.5	200	0	7.5	210
6000	100	2	0	7.5	201	0	7.5	211
7400	123	2	0	7.5	201	0	7.5	211
8800	147	2	0	7.5	201	0	7.5	211
10200	170	3	0	7.5	200	0	7.5	210
11600	193	3	0	7.5	197	0	7.5	207
13000	217	4	0	7.5	194	0	7.5	204
14400	240	4	0	7.5	192	0	7.5	202
46400	773	13	1	7.5	162	0		
86400	1440	24	1	7.5	140	0		
172800	2880	48	2	7.5	140	0		
259200	4320	72	3	7.5	140	0		
345600	5760	96	4	7.5	140	0		
432000	7200	120	5	7.5	140	0		
864000	14400	240	10	7.5	140	0		
1296000	21600	360	15	7.5	140	0		
1728000	28800	480	20	7.5	140	0		
2160000	36000	600	25	7.5	140	0		
2592000	43200	720	30	7.5	140	0		

The model predictions for the base case are listed in Table 6.5-4. After 30 days, a total of 619 kg of $\text{NaAlSi}_3\text{O}_8$ was precipitated along with 51.2 kg of AlOOH and 595.3 kg of $\text{Ca}_3(\text{PO}_4)_2$. The elemental releases leading to these precipitates have been plotted in Figure 6.5-1. The

contribution of each containment material to each elemental release has also been indicated in the figure. Overall, submerged aluminum was responsible for 2.4% of the total mass release, while un-submerged aluminum contributed 14.2 percent. CalSil and E-glass contributed 70.6% and 12.8%, respectively.

The contribution of each containment material to each of the precipitates is also plotted in Figure 6.5-2. The submerged aluminum was the source of 4.1% of the precipitate mass and un-submerged aluminum added 24.1% of the total. CalSil was the largest contributor at 62.2%, and the E-glass added only 9.6% of the total precipitate mass.

Table 6.5-4: Elemental Releases and Precipitation for Base Case

End of Interval (hrs)	Average Interval pH	Average Temp (°F)	Ca Release (kg)	Si Release (kg)	Al Release (kg)	NaAlSi ₃ O ₈ Precipitate (kg)	AlOOH Precipitate (kg)	Ca ₃ (PO ₄) ₂ Precipitate (kg)
0.01	5.6	217	0.03	0.05	0.13	0.2	0.3	0.07
0.02	5.6	217	0.06	0.12	0.30	0.4	0.6	0.16
0.03	5.6	212.5	0.13	0.24	0.59	0.8	1.1	0.33
0.05	5.6	213.5	0.19	0.37	0.89	1.1	1.7	0.50
0.06	5.6	214	0.22	0.41	0.99	1.3	1.9	0.56
0.11	6.15	217	0.43	0.91	2.12	2.8	4.1	1.10
0.17	6.95	222	0.63	1.58	3.46	4.9	6.6	1.62
0.22	7.3	226.5	0.82	2.38	5.03	7.4	9.5	2.13
0.28	7.45	229.5	1.02	3.27	6.76	10.2	12.7	2.64
0.33	7.5	230	1.22	4.18	8.52	13.0	15.9	3.14
0.39	7.5	226	1.41	5.01	10.06	15.6	18.8	3.64
0.44	7.5	216.5	1.60	5.68	11.19	17.7	20.8	4.12
0.50	7.5	205.5	1.78	6.20	11.95	19.3	22.1	4.59
0.89	7.5	193.5	3.04	8.94	15.64	27.8	28.4	7.85
1.28	7.5	193.5	4.27	11.64	22.01	36.2	40.6	11.00
1.67	7.5	200.5	5.44	14.78	29.98	46.0	56.1	14.04
2.06	7.5	201	6.58	17.91	38.07	55.7	71.8	16.97
2.44	7.5	201	7.67	20.98	46.16	65.3	87.6	19.80
2.83	7.5	200.5	8.73	23.96	54.11	74.5	103.1	22.53
3.22	7.5	198.5	9.76	26.75	61.58	83.2	117.7	25.18
3.61	7.5	195.5	10.76	29.29	68.37	91.1	131.0	27.76
4.00	7.5	193	11.74	31.63	74.62	98.4	143.2	30.28
12.89	7.5	177	35.20	65.61	75.58	204.1	121.2	90.83
24.0	7.5	151	63.65	75.93	75.85	236.2	114.4	164.21
48.0	7.5	140	132.05	88.75	76.23	276.0	106.2	340.69
72.0	7.5	140	174.79	101.22	76.60	314.8	98.2	450.96
96.0	7.5	140	201.50	113.36	76.98	352.5	90.4	519.86
120.0	7.5	140	218.18	125.16	77.35	389.3	82.8	562.91
240.0	7.5	140	230.73	182.62	79.23	567.9	46.2	595.29
360.0	7.5	140	230.73	199.03	81.11	619.0	38.7	595.29
480.0	7.5	140	230.73	199.03	82.99	619.0	42.8	595.29
600.0	7.5	140	230.73	199.03	84.87	619.0	47.0	595.29
720.0	7.5	140	230.73	199.03	86.75	619.0	51.2	595.29

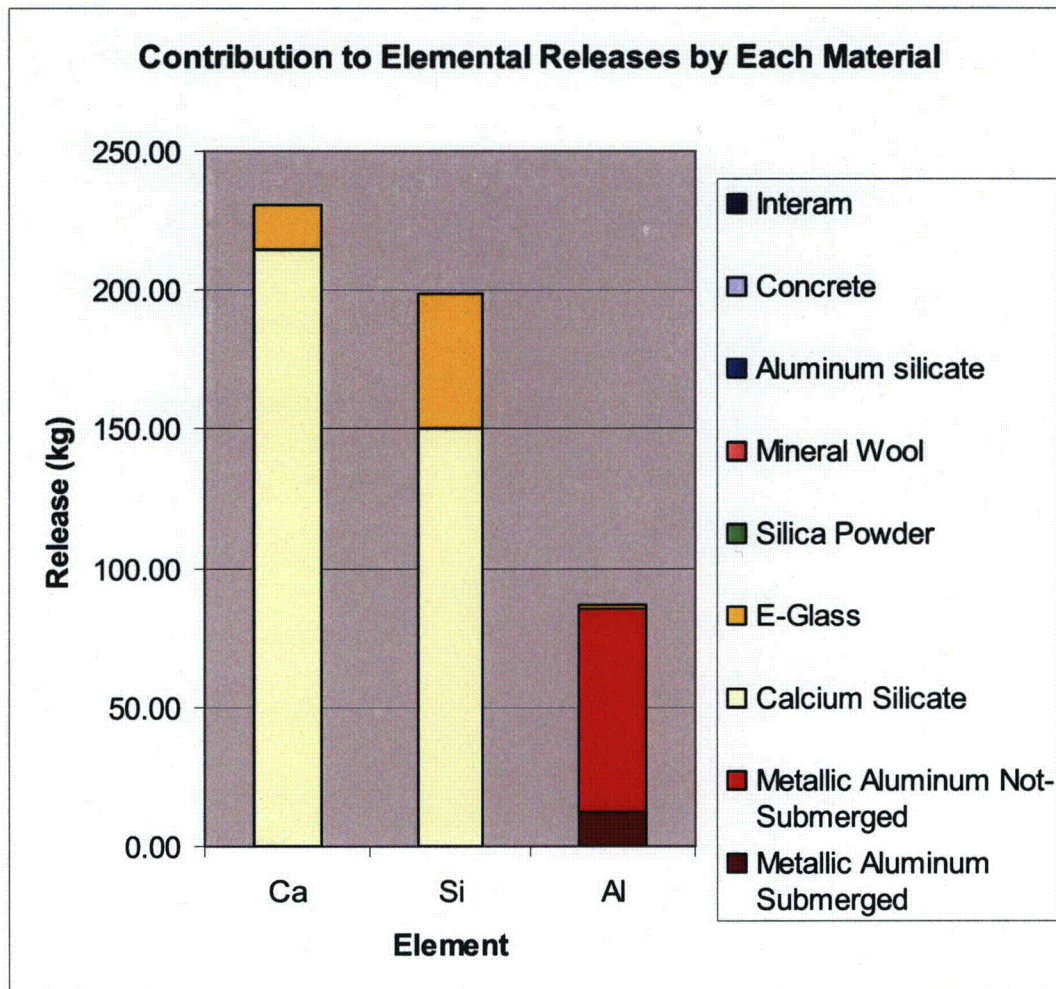


Figure 6.5-1: Predicted Elemental Releases by Source Material (Base Case)

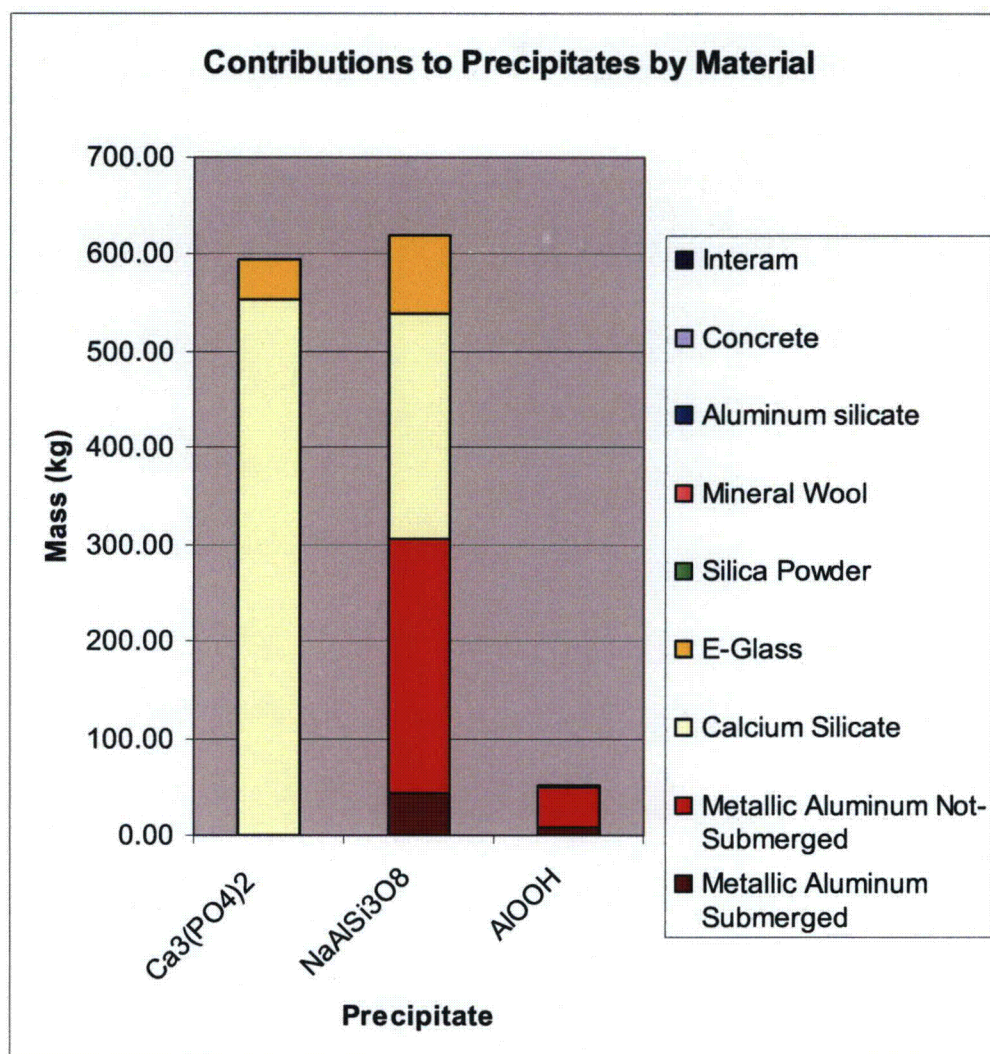


Figure 6.5-2: Predicted Precipitation by Source Material (Base Case)

Most of the aluminum was released during the spray phase of the LOCA when temperatures were high and a large area of aluminum was exposed to the spray solution. This is shown in Figure 6.5-3.

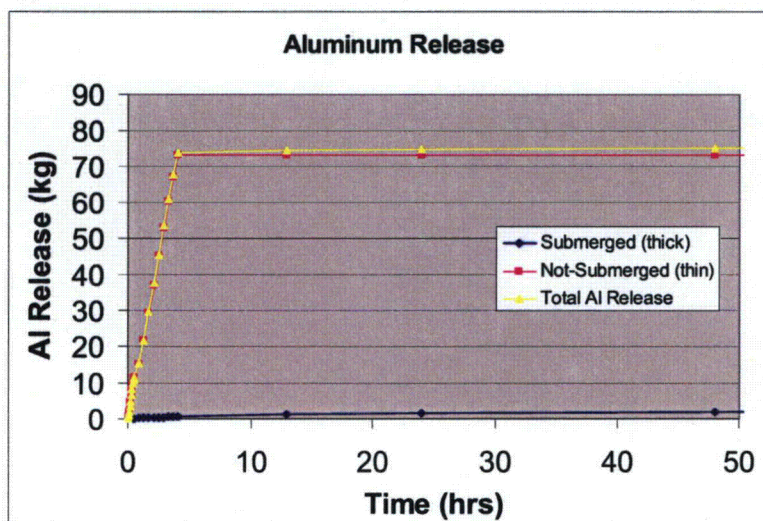


Figure 6.5-3: Predicted Release of Aluminum with Time (base case)

Most of the CalSil dissolution also took place shortly after the LOCA. In fact, the model indicated that by 120 hours, 94 percent of the CalSil that was transported to the sump had dissolved and that by 240 hours, all CalSil was in solution. The release of calcium from CalSil showing the rapid early release is shown in Figure 6.5-4.

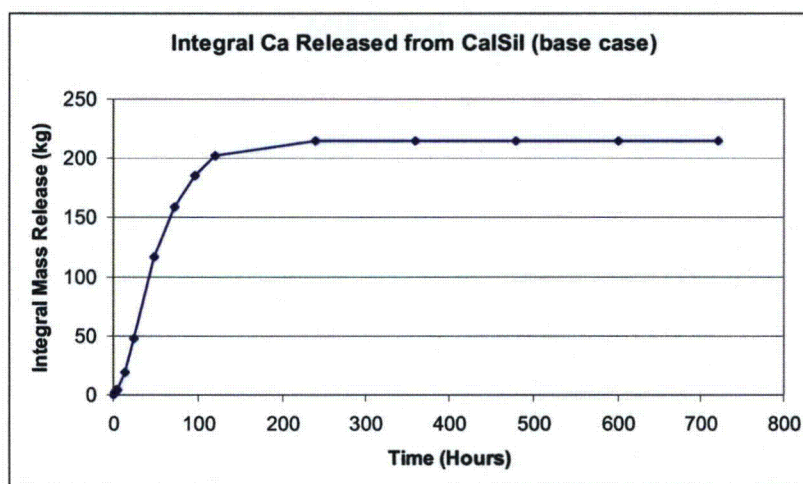


Figure 6.5-4: CalSil Release with Time Showing Complete Dissolution (base case)

The complete dissolution of CalSil predicted by the chemical effects model is consistent with the latest dissolution tests conducted at Argonne National Laboratory. These tests discovered that when CalSil was added to simulated coolant at 60°C (140°F) to a concentration of either 0.5 or 1.5 g/l, complete dissolution took place in about 100 hours. This was true, even when TSP was added to the simulated coolant at three separate rates (Reference 6.5-1).

6.5.2 Sensitivity to pH Change

The effect of pH change on precipitate mass was explored using the chemical effects model. Such a pH change could be accomplished in practice by adding or removing TSP mass from the containment baskets. In the model, the pH vs. time curves were modified by changing the maximum pH while keeping the minimum pH constant at a value of 5.6. Intermediate pH values were kept at the same relative location between the maximum and the minimum as in the base case. The maximum pH was varied between 5.6 and 10.5. The results are shown in Figure 6.5-5.

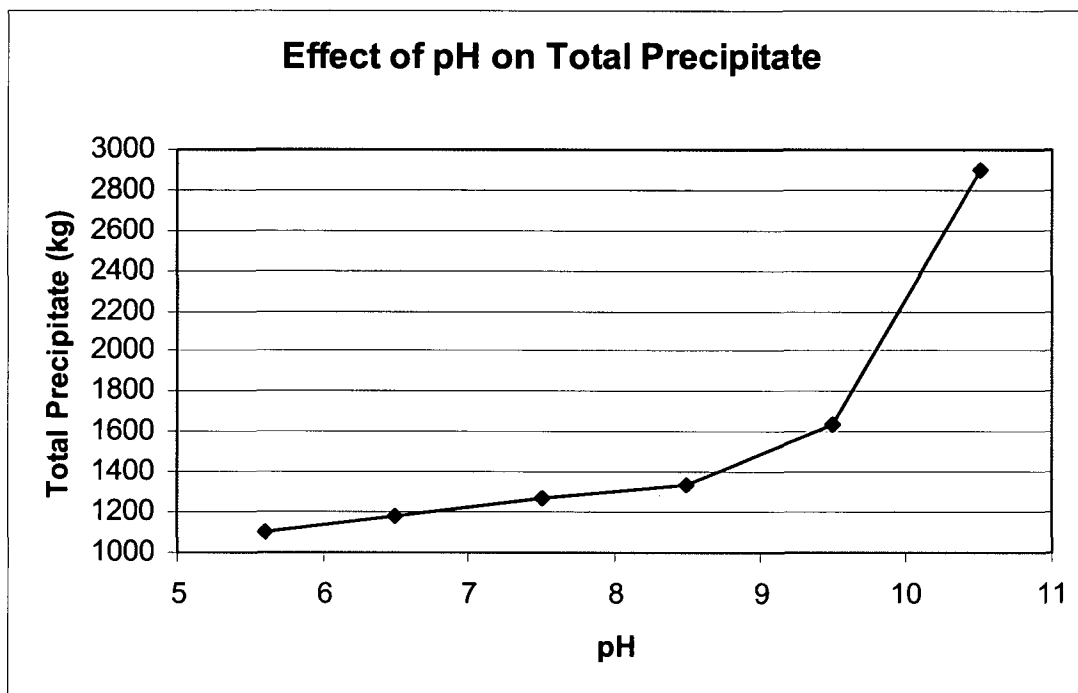


Figure 6.5-5: Effect of pH Variation on Total Precipitate Mass

The amount of precipitate generated increased slowly between pH values of 5.6 and 8.5. The precipitate mass total increased more rapidly between a pH of 8.5 and 10.5. The corrosion of aluminum during the spray phase was the main contributor to precipitate increase at high pH values. The CalSil dissolves completely during the 30 day post-LOCA period at pH values between 5.6 and 8.5. At pH values above pH 8.5, the CalSil dissolution decreases, but this benefit is opposed by the steep increase in aluminum corrosion.

6.5.3 Sensitivity to Temperature Change

The effect of changing temperature was explored in a manner similar to the pH sensitivity determination just described. The minimum temperature of 140°F was fixed and the maximum temperature was varied up to a value of 270°F. Intermediate temperature values were kept at the same relative location between the maximum and minimum as in the base case.

The results of the temperature sensitivity study are shown in Figure 6.5-6. Increasing the maximum containment temperature increased the amount of precipitate generated. The total percentage change was relatively small at about 20 percent. The effect was due mainly to the increase of aluminum corrosion with temperature. The CalSil completely dissolved at all temperatures before the 30 day recirculation time was complete.

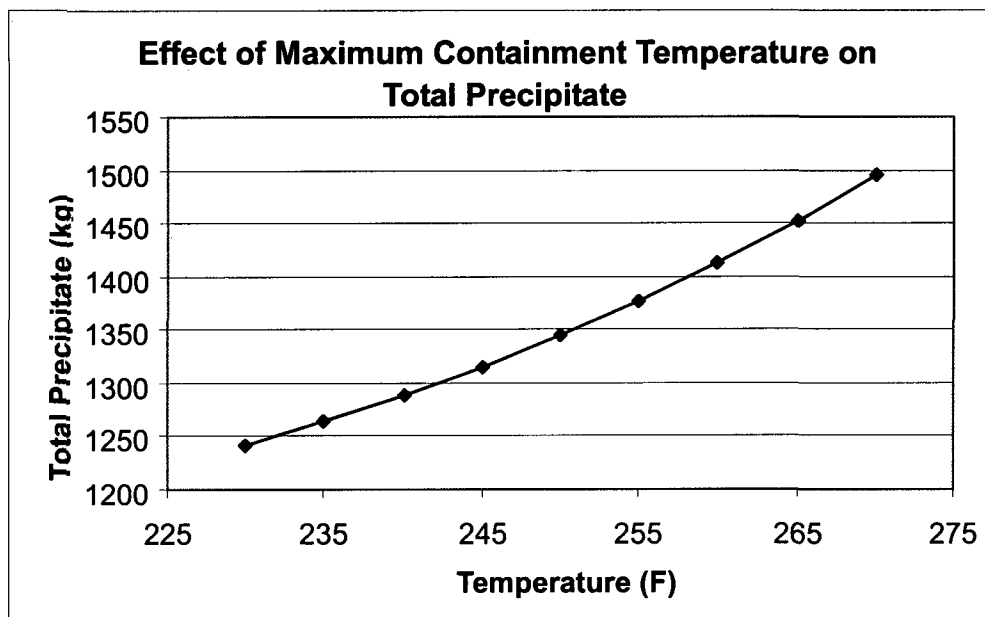


Figure 6.5-6: Effect of Temperature Variation on Total Precipitate Mass

6.5.4 Sensitivity to Buffering Agent

A change in buffer type from TSP to Borax was simulated by taking the TSP out of the materials list in the chemical effects model. The pH and temperature profiles were maintained at the base case levels. About half of the precipitation was observed with Borax compared to TSP as shown in Figure 6.5-7. Removing the TSP did not completely eliminate precipitation because of the significant aluminum corrosion. The aluminum reacted with the silica released from the CalSil to form sodium aluminum silicate. The relative amounts of sodium aluminum silicate and aluminum oxide hydroxide are shown in Figure 6.5-8.

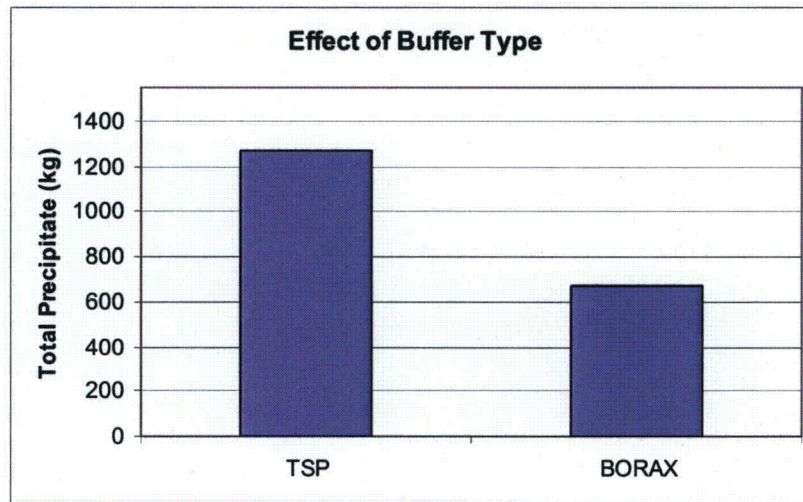


Figure 6.5-7: Effect of Changing Buffer on Total Precipitate Mass

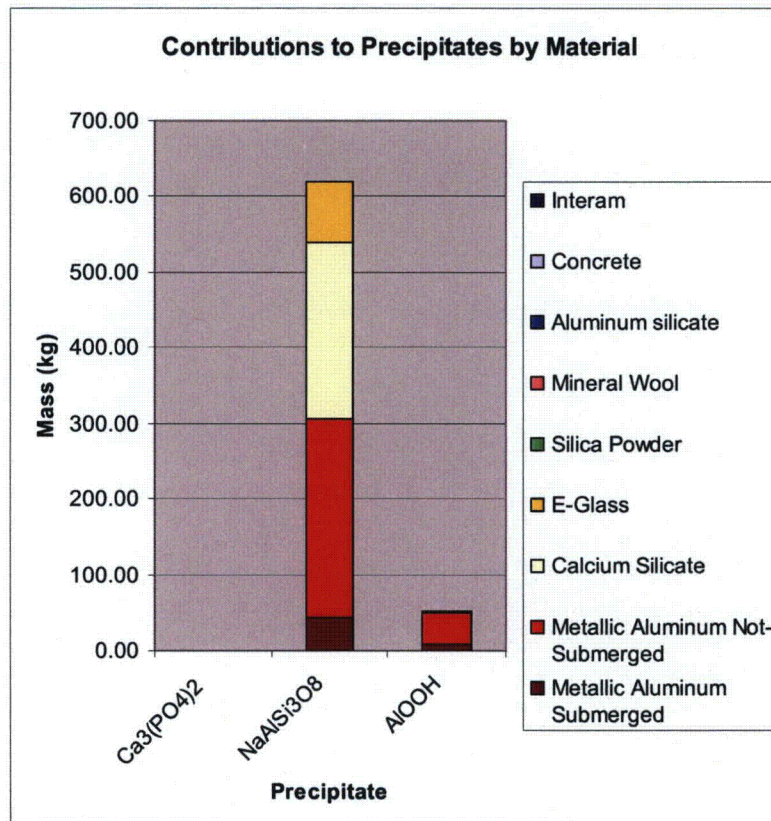


Figure 6.5-8: Effect of Changing Buffer on Precipitate Formation

6.5.5 Sensitivity to Exposed Concrete Surface Area

The containment survey that was used as the basis for the sensitivity study did not list any exposed and submerged concrete area, but since most plants have this source, the model was run with varying amounts of concrete exposed. The results are shown in Figure 6.5-9.

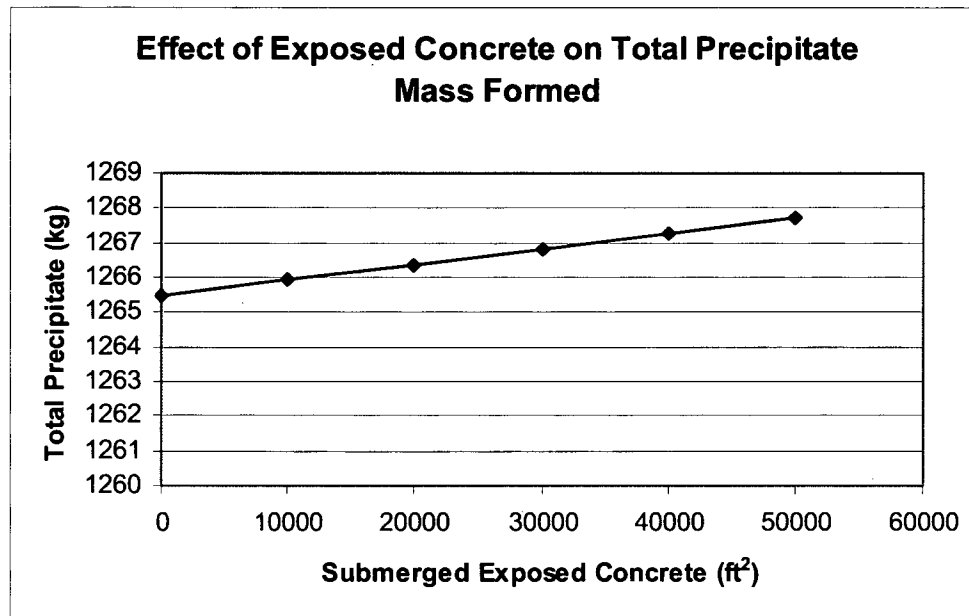


Figure 6.5-9: Effect of Adding Exposed Concrete to Base Case Materials

The precipitation of materials from concrete dissolution appears to be negligible even when high exposed surface areas are input.

6.5.6 Reference

- 6.5-1 J. Oras, J. H. Park, K. Kasza, K. Natesan, W. J. Shack, Chemical Effects/Head-Loss Testing, Quick Look Report, Tests ICET-3-4 to 11, January 20, 2006.

7.0 PARTICULATE GENERATOR

7.1 PURPOSE

The purpose of the particulate generator is to create prototypical solid chemical products (precipitates) for sump screen performance testing at vendor test facilities. After generation in the unit, the chemical products may be treated as another class of inert debris for strainer testing purposes. The system generally comprises one or more chemical reaction tanks, one or more precipitate transfer pumps, a precipitate mix holding tank, and interconnecting hoses/piping and valves. The system is intended to be operated using normal potable water at ambient temperature, although operation at elevated temperature may be conducted if desired.

The filtration and settling behaviors of the key precipitates are influenced by the amorphous and hydration properties of the materials. These properties are based on the chemical nature of the specific precipitates and are due to the fact that the species are formed *in situ*¹. These exact behaviors may not result if crystalline, non-hydrated solid starting materials are used to simulate the precipitates (for example, use of solid calcium phosphate). Also, other solid starting materials may not provide the same filtration, agglomeration and settling characteristics (for example, use of aluminum sulfate or alum in place of aluminum hydroxide). Therefore, if crystalline, non-hydrated, or other manufactured solid starting materials are to be used in sump screen testing, it is suggested that testing be performed to demonstrate the acceptability of the starting materials for simulating the amorphous and hydrated materials generated in the bench testing. If no testing of the filtration and settling characteristics of these materials is planned, it is recommended that the particulates be generated as described below to ensure materials with prototypical behaviors are used in screen testing. However, if vendors prefer to use manufactured materials in screen testing, the settling and filtration characteristics of these materials may be compared to the acceptance criteria presented in Section 7.8.

7.1.1 Reference

- 7.1-1 Giulietti, M., et al., "Industrial Crystalization and Precipitation from Solutions State of the Technique," Braz. J. Chem. Eng., Vol. 18(4), December 2001.

7.2 FUNCTIONAL REQUIREMENTS

7.2.1 General

The detailed design of the particulate generator is dependent on the size of the screen test facility and the plant-specific precipitate mix to be tested. For a given screen test facility, the expected variations in design would generally be limited to the number of chemical mixing tanks and transfer pumps required. Therefore, a generator constructed for a plant-specific test can be readily modified as required for use in additional plant-specific test programs.

All wetted materials used to construct the system must be chemically resistant to short-term exposure to the reactant chemicals used to prepare the precipitates, as well as long-term exposure

to oxygenated water. Suitable materials include austenitic stainless steel, high density polyethylene (HDPE), polytetrafluoroethylene (PTFE, e.g., Teflon), polypropylene, polyvinylchloride (PVC), Norprene, ethylene-propylenediene monomer (EPDM; for hose lining) and vinyl. Wetted components constructed of carbon/low alloy steel, zinc, aluminum or brass should not be used. The system is intended to be operated using normal potable water at ambient temperature, although operation at elevated temperature may be conducted if desired. Construction materials should be selected consistent with the desired test temperature range.

7.2.2 Equipment Details

Chemical Mixing and Holding Tanks

Chemical mixing tank(s) should be sized to contain at least 20 percent of the screen test system volume. Alternatively, smaller tanks may be used and particulates may be generated in several batches. The holding tank should be sized to hold the combined contents of the mixing tank(s). The tanks should be fitted with removable lids or have lidded openings for chemical additions and tank cleaning. Cone bottom tanks are recommended to facilitate complete precipitate transfer. The tank should be fitted with a mixer sized sufficiently to create a vortex in the tank. Air or electrically powered mixers may be used.

Transfer Pumps

The pump used to transfer the precipitates from the chemical reaction and holding tank(s) should be sized to transfer the tank contents in 20 minutes or less. Although the type of pump is not critical, peristaltic or diaphragm pumps are preferred to facilitate transfer of solid material and post-use clean out. Air or electrically powered pumps may be used.

Interconnections, Valves and Fittings

It is recommended that hose/flexible tubing be used to facilitate reconfiguring the system for plant-specific testing. To facilitate transfer of precipitate slurries and system clean out, ball valves should be used. The system should be constructed to minimize crevices and dead legs/low flow areas to facilitate system clean out.

Cleaning

After each use, the particulate generator should be rinsed with water and visually inspected to verify all particulates have been rinsed from the components. Special attention should be paid to valves, pumps and other areas where particulates may be trapped.

Waste Disposal

All precipitates and liquids should be disposed of in accordance with applicable federal, state and local laws. Typically, the waste can be sent directly to the sanitary sewer system with no pretreatment. However, the acceptability of this path must be determined locally.

7.3 GENERATION OF CHEMICAL PRECIPITATES

7.3.1 General

To prepare the precipitates, add ambient temperature water to the reaction tank and initiate stirring. Slowly add the reactants individually in the specified order, and allow them to dissolve completely before adding additional reactants. Chemical reactants may optionally be pre-dissolved in water prior to addition to the reaction tank. After reactant addition, maintain mixing for a minimum of one hour to allow chemical reactions to go to completion. Obtain a representative sample of the precipitate slurry for testing. Dilute the sample as directed below. Measure the pH, time to settle, and 1-hour wet volume of the precipitate. Time to settle is the time required to achieve less than 5 percent change in volume over a 30-minute period. The pH should be greater than 6.5 to verify complete reaction of the acidic metal salts. After the precipitates are determined to be acceptable, they may be injected directly into the screen test system.

Hardness minerals (e.g., calcium, magnesium, etc.) will not inhibit precipitate formation, nor affect the physical characteristics of the precipitates. However, these minerals may co-precipitate with the intentionally added metals (aluminum or calcium). Based on the low concentration of hardness minerals relative to the concentration of intentionally added metals, the contribution to the total quantity of precipitates generated would be negligible.

7.3.2 Precipitate Formation

Aluminum Oxyhydroxide

For each 100 grams of aluminum oxyhydroxide precipitate, add 625 grams of aluminum nitrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$). After the aluminum salt has dissolved, add 200 grams of sodium hydroxide (NaOH). Obtain a sample and dilute as required to obtain a precipitate concentration of 2.1 to 2.3 grams per liter. After one hour, the resultant precipitate should have a minimum settling volume of 6.0 milliliters for a 10 ml sample.

To achieve prototypical settling behavior, the concentration of aluminum oxyhydroxide in a single mixing tank should not exceed 11 grams per liter.

Calcium Phosphate

For each 100 grams of calcium phosphate precipitate, add 170 grams of calcium acetate. After the calcium salt has dissolved, add 245 grams of trisodium phosphate (TSP). Obtain a sample and dilute as required to obtain a precipitate concentration of 0.9 to 1.1 grams per liter. After one hour, the resultant precipitate should have a minimum settling volume of 5.0 milliliters for a 10 ml sample.

To achieve prototypical settling behavior, the concentration of calcium phosphate in a single mixing tank should not exceed 5 grams per liter.

Sodium Aluminum Silicate

The settling rate and filtration characteristics of sodium aluminum silicate are sufficiently similar to aluminum oxyhydroxide that aluminum oxyhydroxide may be used in lieu of sodium aluminum silicate. This approach simplifies precipitate generation and avoids use of sodium silicate, which may be considered hazardous. In the event it is necessary to form sodium aluminum silicate, the instructions are provided below.

For each 100 grams of sodium aluminum silicate precipitate, add 143 grams of aluminum nitrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$). After the aluminum salt has dissolved, slowly add 520 milliliters of sodium silicate solution (40% Na_4SiO_4). Obtain a sample and dilute as required to obtain a precipitate concentration of 9.6 to 9.8 grams per liter. After one hour, the resultant precipitate should have a minimum settling volume of 6.0 milliliters for a 10 ml sample.

To achieve prototypical settling behavior, the concentration of sodium aluminum silicate in a single mixing tank should not exceed 11 grams per liter.

For head loss tests in which the objective is to keep chemical precipitate suspended (i.e., by tank agitation):

Sodium aluminum silicate and aluminum oxyhydroxide precipitate settling shall be measured within 24 hours of the time the surrogate will be used and the 1-hour settled volume shall be 6 ml or greater and within 1.5 ml of the freshly prepared surrogate. Calcium phosphate precipitate settling shall be measured within 24 hours of the time the surrogate will be used and the 1 hour settled volume shall be 5 ml or greater and within 1.5 ml of the freshly prepared surrogate. Testing shall be conducted such that the surrogate precipitate is introduced in a way to ensure transportation of all material to the test screen.

For head loss testing in which the objective is to settle chemical precipitate and other debris:

Aluminum containing surrogate precipitate that settles equal to or less than the 2.2 g/l concentration line shown on Figure 7.6-1 (i.e., 1- or 2-hour settlement data on or above the line) is acceptable. The settling rate shall be measured within 24 hours of the time the surrogate precipitate will be used.

7.4 PROOF-OF-PRINCIPLE APPARATUS

A pilot scale particle generator was constructed and tested to verify proper operation of the conceptual unit. A photograph of the assembled system is provided in Figure 7.4-1 and a diagram is provided as Figure 7.4-2. The laboratory system was constructed using the following components:

- Three 5-gallon capacity open topped, conical bottom HDPE tanks. Two tanks were used as chemical mixing tanks, and the third tank was used as the holding tank. Each tank was fitted with a HDPE lid and was mounted on an enamel coated steel stand. The chemical mixing tanks were fitted with a 1/2-inch polypropylene faucet in the side to facilitate decanting.
- One stand mounted, variable speed, 10,000 rpm electric mixer for each tank. The mixers operated on 115 VAC/60 Hz power, and were fitted with 12-inch stainless steel shafts with 1-3/8-inch stainless steel propellers.
- One electrically powered peristaltic pump to transfer the contents of each tank. The pumps had a maximum flow rate of 2.2 gpm, and operated on 115 VAC/60Hz power. The wetted parts were constructed of PVC and Norprene.
- One 5-gallon capacity cylindrical, flat bottom, open top HDPE tank that served as the receiver tank to represent the strainer test system.
- The tanks/pumps were connected using 1/2-inch inner diameter, smooth bore nylon tubing.

All system components were procured as standard commercial items from McMaster-Carr.

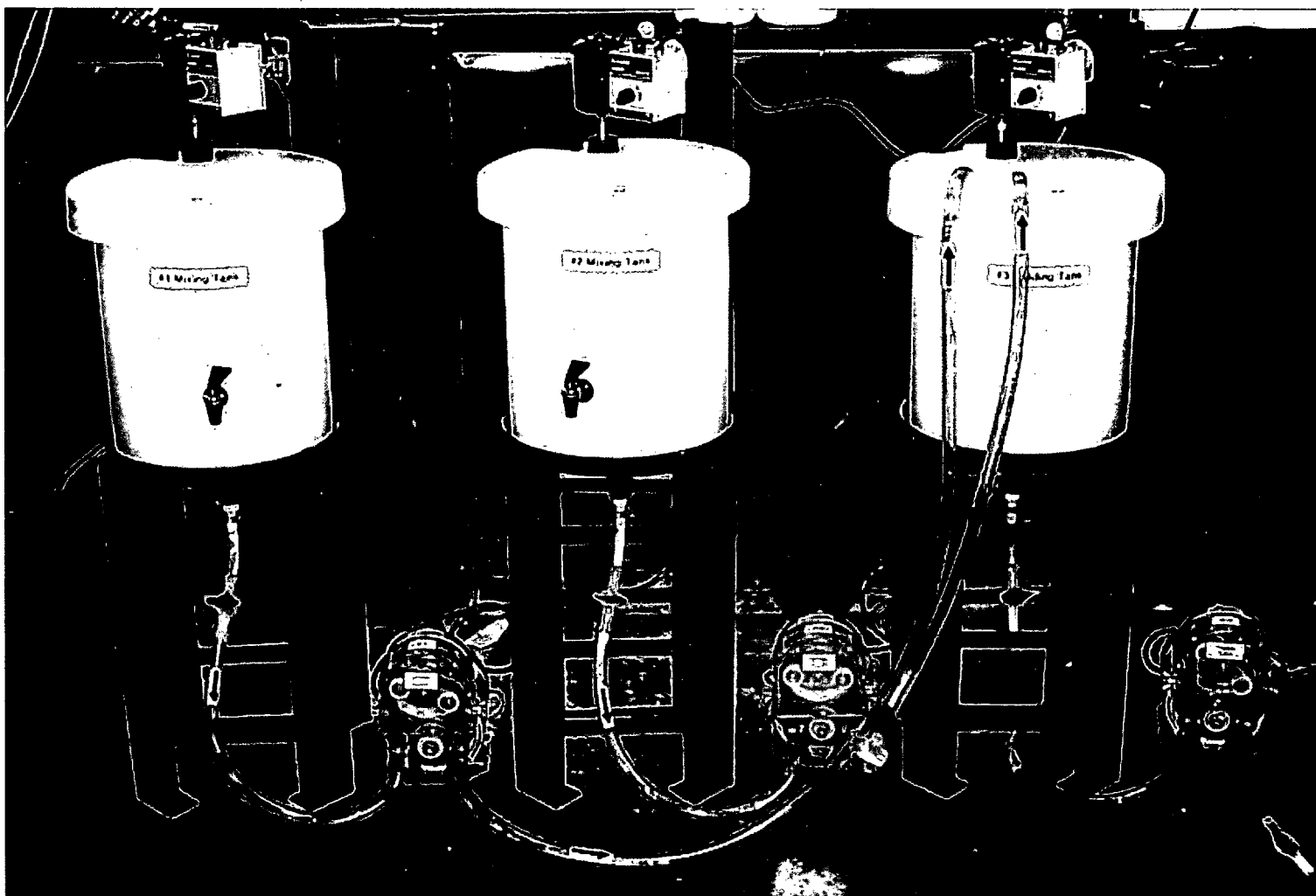
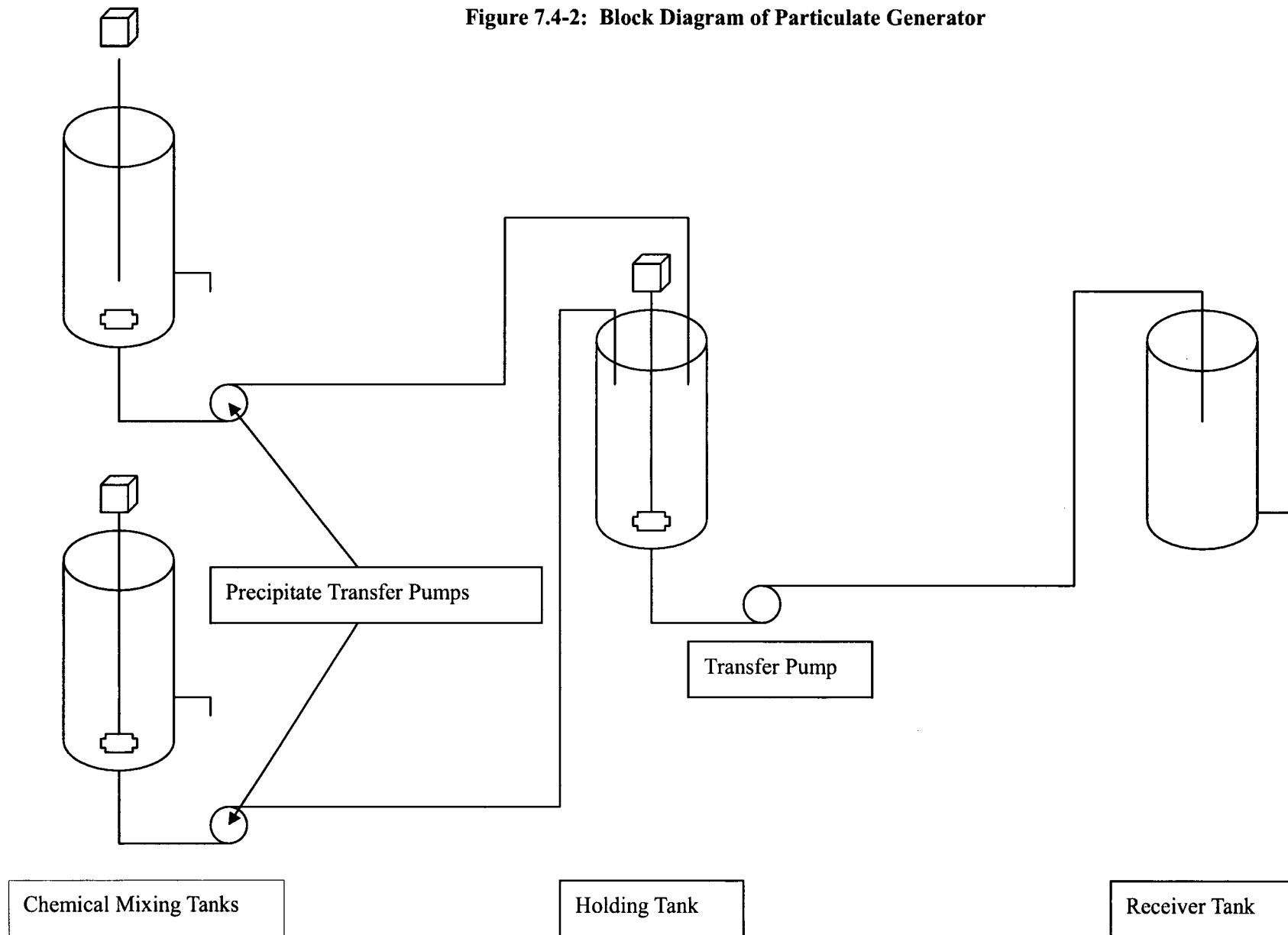


Figure 7.4-1: Photograph of Assembled Pilot Scale Particulate Generator

Figure 7.4-2: Block Diagram of Particulate Generator

7.5 PARTICULATE GENERATOR QUALIFICATION TESTING

Testing was performed to verify expected operation of the particulate generator. Calcium phosphate particulate was generated to achieve a final particulate concentration of 1.0 grams per liter in a simulated strainer test loop. Aluminum oxyhydroxide was generated to achieve a final particulate concentration of 2.2 grams per liter in a simulated test loop. Due to the similarity of the physical characteristics and preparation techniques of sodium aluminum silicate with those of aluminum oxyhydroxide, qualification testing of sodium aluminum silicate in the particulate generator was not considered necessary. The particulates were generated in accordance with the guidance provided in the preceding section. All testing was performed using potable water (Churchill, PA) with a temperature of about 55°F.

7.5.1 Calcium Phosphate

To prepare the particulate, the chemical mixing tank was filled with two gallons of water. Mixing was initiated, and 64.5 grams of calcium acetate monohydrate was slowly added, followed by addition of 92.8 grams of trisodium phosphate dodecahydrate. These addition quantities were selected to obtain a total of 38 grams of calcium phosphate in order to achieve a diluted concentration of 1.0 grams per liter in a simulated 10-gallon test system volume.

The solution was mixed for 60 minutes, and then mixing was secured. The solution was sampled and analyzed for pH. The pH of the potable water was also measured for reference. The results of these analyses are provided in Table 7.5-1.

A one gallon aliquot of the holding tank contents was transferred to a tank containing 5 gallons of water to simulate transfer of the particulate into a test loop. The resultant diluted precipitate was sampled and analyzed for pH, time to settle, settling volume and filterability. The settling and filtration characteristics were consistent with those observed during bench-scale testing of the precipitates generated from addition of phosphate to solutions containing calcium from dissolution of CalSil and concrete.

Table 7.5-1: Analysis Results for Samples Obtained during Calcium Phosphate Generation Test

Sample Description	pH	Conductivity (μ S/sm)	2-hr Settled Volume (ml)
Potable Water	8.02	254	NA
Mixing Tank	9.05	NM*	NM*
Diluted	8.69	NM*	5.6

*NM = Not measured

7.5.2 Aluminum Oxyhydroxide

To prepare the particulate, the chemical mixing tank was filled with two gallons of water. Mixing was initiated, and 526 grams of aluminum nitrate nonahydrate was slowly added, followed by addition of 168 grams of sodium hydroxide. These addition quantities were selected to obtain a total of 84 grams of aluminum oxyhydroxide to achieve a diluted concentration of 2.2 grams per liter in a simulated 10-gallon test system volume.

The solution was mixed for 60 minutes, and then mixing was secured. A sample was obtained and analyzed for pH. A one gallon aliquot of the holding tank contents was transferred to a tank containing five gallons of water to simulate transfer of the particulate into a test loop. The resultant diluted precipitate was sampled and analyzed for pH, time to settle, settling volume and filterability. The settling and filtration characteristics were consistent with those observed during bench-scale testing of the precipitates generated from corrosion of aluminum metal.

Table 7.5-2: Analysis Results for Samples Obtained during AlOOH Generation Test

Sample Description	pH	1-hr Settled Volume (ml)
Mixing Tank	7.10	NM
Diluted	7.40	5.8

*NM = Not measured

7.6 EFFECT OF CONCENTRATION OF GENERATED PRECIPITATES ON SETTLING CHARACTERISTICS

Initial particulate generation runs showed that, after dilution, highly concentrated precipitates settled at atypically high rates. Therefore, bench scale testing was performed to determine the settling characteristic of generated precipitates as a function of mix tank concentration. For aluminum oxyhydroxide, solutions of 11, 16.5 and 22 grams per liter were prepared. The concentrated solutions were diluted to 2.2 grams per liter. For calcium phosphate, solutions of 5, 10, 15 and 20 grams per liter were prepared, and then diluted to 1 gram per liter. The settling rates of the resultant particulate mixtures were measured in 10-ml settling tubes. The results of these tests are shown in Figures 7.6-1 and 7.6-2. These results show that to achieve reasonably prototypical setting behavior, the mix tank concentration of aluminum oxyhydroxide should not exceed 11 grams per liter, and the mix tank concentration of calcium phosphate should not exceed 5 grams per liter.

Figure 7.6-1: Settling Rate of 2.2 g/L AlOOH as a Function of Mix Tank Concentration

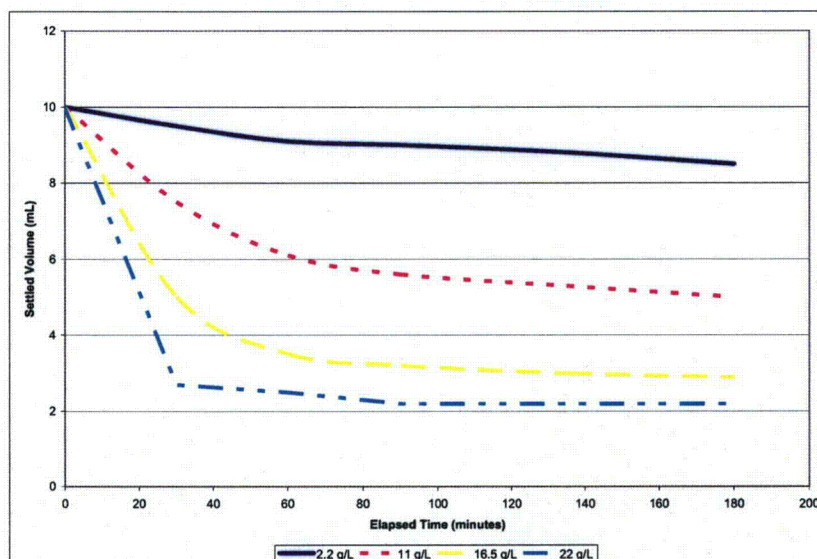
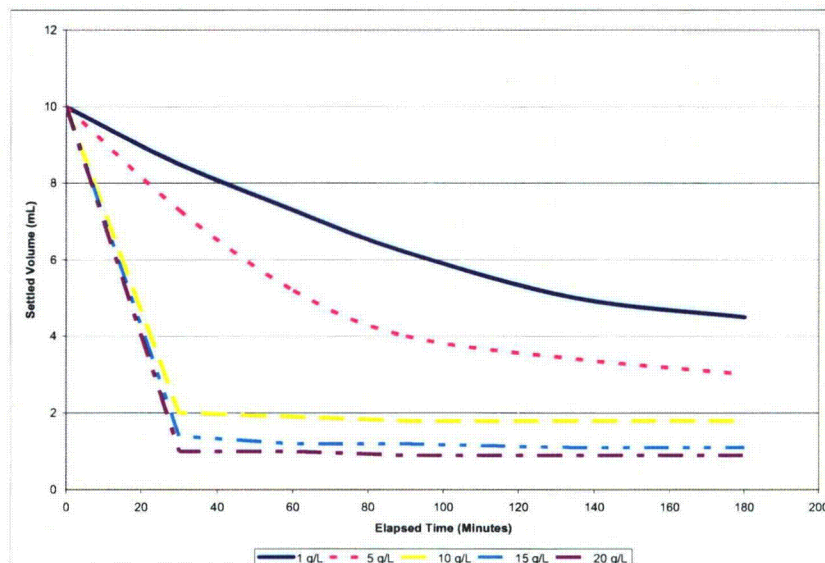


Figure 7.6-2: Settling Rate of 1.0 g/L Calcium Phosphate as a Function of Mix Tank Concentration

7.7 CONCLUSIONS FROM PARTICULATE GENERATOR TESTS

Testing of the particulate generator demonstrated that simulated particulates can be successfully generated for use in sump screen testing. Generation of the particulates is generally straightforward, and can be performed using readily available equipment and materials. The testing confirmed that the quality and temperature of the water used to prepare the particulates, and that used in the screen test loop, is not critical. No special water chemistry control is required to use the generated particulates in screen testing. The most critical parameter determined during the testing was the limitation on the degree of concentration of the particulates in the mixing tank. In the event that large quantities of particulates are required, the particulates may be prepared in batches or in multiple mixing tanks.

7.8 CRITERIA FOR ALTERNATIVE PRECIPITATES TO BE USED IN SCREEN TESTING

In the event a vendor desires to use alternative materials, the 1-hour settling rate and filtration characteristics of the proposed alternatives must be determined and be verified to meet the minimum acceptance criteria provided in Table 7.8-1. In such cases, it may be necessary to pre-soak the material in water for several hours/days to ensure the proper degree of hydration is obtained.

Table 7.8-1: Minimum Physical Characteristics of Surrogate Precipitates

Precipitate	1-hour Settled Volume (ml)	Metal Concentration (ppm)	Filterability K_f
Sodium Aluminum Silicate	>6.0	1000 ppm Al Equivalent	0.19
Calcium Phosphate	>5.0	400 ppm Ca Equivalent	0.03
Aluminum Oxyhydroxide	>6.0	1000 ppm Al Equivalent	0.20

8.0 PLANT-SPECIFIC APPLICATION

8.1 TRANSITION TO SCREEN VENDOR TESTING

Each plant, given their plant-specific containment material concentrations, pH, and temperatures post-accident, can use the enclosed information to determine the types and amounts of chemical precipitates which may form and be exposed to the sump screen.

In order for plants to utilize the bench testing results, a spreadsheet containing the chemical model developed to allow for a plant-specific prediction of precipitate formation is provided. Guidance is given in Section 8.2 for utility engineers to input their plant-specific containment material amounts, recirculation water volume, post-accident sump and spray pH transients, post-accident sump and spray temperature transients, and to indicate if trisodium phosphate (TSP) is used as a buffering agent. A key issue in a plant's use of the chemical model is the accuracy of the input, especially the temperature and pH transients post-accident.

Once this input has been supplied, the chemical model predicts the types and amounts of precipitates formed given a plant's post-accident conditions. The main chemical precipitates of concern per the WOG chemical effects testing are aluminum oxyhydroxide, sodium aluminum silicate, and calcium phosphate. Aluminum oxyhydroxide is a concern for all plants which contain aluminum either impacted by the spray or submerged in the containment sump pool; however, for plants with high silicon releases, i.e., large amounts of fiberglass, sodium aluminum silicate may be formed instead of aluminum oxyhydroxide and thus is present in larger quantities. Note that calcium phosphate is only a concern for plants which use TSP as a buffering agent.

The chemical model output yields the types and amounts of chemical precipitates which should be included in plant-specific testing of replacement sump screens. Screen vendors may either obtain surrogates for the precipitates for screen testing or generate the precipitates per the guidance provided in Section 7.0. Section 7.0 contains both a description of the equipment setup and the chemical recipes necessary to generate the precipitates formed during the chemical effects bench testing. If screen vendors choose to use surrogate materials for screen testing, additional testing such as settling and pressure drop tests must be performed to confirm that the behavior of the surrogates meets the criteria provided in Section 7.8.

The chemical model predicts the total amount and types of precipitates which may form post-accident under plant-specific conditions. Once representative precipitates have been obtained, the amount of precipitates for use in screen testing should be scaled to the size of the test screen, similar to the method used for any other debris source. Then the impact of the precipitates on screen head loss may be evaluated.

8.2 DIRECTIONS FOR USE OF CHEMICAL MODEL

This section provides directions for plant-specific use of the chemical model to predict the quantity and types of precipitates which may form post-accident. See Appendix D for the detailed equations used in the chemical model spreadsheet.

The first several worksheets of the supplied Excel file are the only ones for which plant-specific data needs to be input. The later worksheets are used to calculate the mass release of the aluminum, calcium, and silicon from the containment materials. From these mass releases, the quantity of each precipitate formed is determined in the "Results Table" spreadsheet from the most chemically stable compounds. The material sources of the elemental mass releases are shown in the "Releases by Material" spreadsheet, and the material sources for the total mass of precipitates which may form are shown in the "Precipitate by Material" spreadsheet.

Worksheet = Instructions

The first worksheet in the spreadsheet provides instructions for filling out the three subsequent spreadsheets with the plant-specific time-temperature and time-pH profiles, the containment material volumes exposed post-accident, and any required plant-specific material density values.

Worksheet = Time Temp pH Input

This worksheet is used to enter the time-temperature profiles, including sump and steam temperature, and time-pH profile in containment post-accident. The values in red on the worksheet should be replaced with plant-specific values. The level of detail is dependent upon that of the plant-specific information. A sensitivity discussion is included in Section 6.5 to evaluate the effect of input variable error on the results.

Column A contains the time in seconds which corresponds to the changing pH and sump and steam temperatures. The time from the beginning of the accident should be entered within the 35 rows. Column B converts this time to minutes by dividing each row entry by 60 sec/min, while Column C then converts to hours by dividing by 60 min/hr. Finally, Column D converts the time to days by dividing by 24 hr/day. In this example calculation, the chemical effects are considered for 30 days following the accident.

Columns E and F contain the sump pH and sump temperature values, respectively, at the corresponding times in Columns A-D. Similarly, Columns H and I contain the data for the spray pH and containment temperature. The entered sump and spray pH values in Columns E and H should be corrected to 25 °C. Most pH calculations have already corrected the pH values to 25 °C. The model assumes that all surfaces which are in contact with the spray are at the containment temperature entered in Column I.

The chemical effects model was developed using data that covered the temperature range of 185°F to 270°F. The model will extrapolate the data to higher or lower temperatures, but correct operation outside of the range has not been verified. Likewise, the pH range of 4.1 to 12 was used in model development, and any use of the model outside this range is not recommended without additional verification.

Column G presents the option to allow the elemental mass already released into the sump solution to impact the dissolution rate from each material containing that element. In order to take credit for this effect on the dissolution rate, the sump solution must be mixed, which is assumed in this example to occur approximately 1 hour after the start of recirculation.

The notes provide guidance on the post-accident transient. For this example, reactor coolant system (RCS) blowdown is assumed to occur at 6 seconds or 0.1 minutes. After RCS blowdown, the temperature of the RCS water dominates the steam temperature and thus influences the pH. Blowdown is assumed to be complete at 180 seconds or 3 minutes. The injection phase starts shortly after at 200 seconds. At this point, the moisture outside of the sump is mostly made up of the containment spray, so the containment temperature is assumed to be that of the spray solution.

The injection phase continues until 1800 seconds or 30 minutes when the recirculation phase begins. Correspondingly, the sump temperature and steam temperature begin to drop significantly. The spray is terminated 4 hours into the transient, while recirculation continues until the end of the calculation. For plants with a different spray duration, the data in Columns H and I may be extended or shortened depending on the length of the spray phase.

Note that if data is entered over a different range of cells than is shown in the example, the worksheets referencing this data must all be changed by adding or subtracting rows accordingly. The easiest approach at this time is to adjust the data to fit into example cell range.

Worksheet = Materials Input

This worksheet is used to input the containment material data, such as that requested on the plant survey, and the recirculation water volume. The materials are divided into the material classes determined for testing. Also, there is a flag to indicate whether or not trisodium phosphate (TSP) is used as a buffering agent.

Column A lists the material classes developed to sort the containment materials by chemical composition. Column B lists the materials within each class. Finally, the amount of each material should be input in Column C using the units listed in Column B. For the insulation material volumes and the exposed concrete surface area, the amount input should be the total amount of material which is either transported to the sump pool or submerged in the sump pool.

Note that if there is a significant amount of concrete debris/dust assumed to be formed, the mass of this concrete debris may be converted to a corresponding surface area using the specific surface area given in Section 5.1.2.1 to be $9.24 \text{ m}^2/\text{g}$. The surface area of this concrete debris can then be added to the exposed surface area of the undamaged concrete.

The model assumes that the amount of precipitate generated from the insulation materials and concrete exposed to the spray will not contribute significantly to the total amount of precipitate formed from the submerged materials. The limited amount of precipitate which does form due to exposure to the spray is expected to become captured within the material and hence will not be transported to the sump pool and subsequently to the sump screen. Alternatively, the model may be rerun with the amount of materials exposed to the spray to determine the additional amount of precipitate formed. If this method is used, the spray pH and temperature profiles must be entered in the columns for the sump pH and temperature.

The aluminum surface area input is separated into two categories: the surface area exposed to the spray (aluminum not-submerged) and the surface area submerged in the sump pool. There is no difference in the corrosion rates for these two categories of aluminum; however, the two categories are exposed to

different pH and temperature profiles affecting the rate of dissolution. For each category of aluminum the mass corresponding to the surface area input should be entered if available. Inputting the aluminum mass limits the total aluminum release to that available. If the mass is not known, a large number may be entered for conservatism.

The sump pool volume should also be entered in Column C. Alternatively, if the total mass of the coolant in the Emergency Core Cooling System (ECCS) is known, this value should be entered in the "Materials Conversions" spreadsheet. Note, for the sump pool volume, sensitivities should be run with both the minimum and maximum recirculation volume in order to determine the more limiting case for each precipitate generated. Sensitivities show that using the minimum recirculation water volume may result in a larger aluminum oxyhydroxide mass, while the maximum recirculation volume provides for greater masses of calcium phosphate and sodium aluminum silicate.

Worksheet = Materials Conversions

This worksheet converts the material amounts input in the previous worksheet to mass for all materials but the aluminum for which the mass was entered on the previous worksheet. The mass (lb) is converted to kg by dividing by the conversion factor of 2.2046 lb/kg. The material densities are obtained from NEI 04-07 (Reference 8.2-1). If these density values are not consistent with plant-specific requirements, the density values may be changed to those required. Once each insulation material volume is converted into mass, the masses in each material class are summed to provide a total plant-specific mass for each tested material.

The recirculation sump pool volume is also converted to mass in this worksheet using the density of boric acid at 185°F. If plants do not know the mass of the recirculation water and hence cannot enter it in Column E, then the density of water at the temperature at which the sump pool volume was determined should be used.

Worksheet = Results Table

This worksheet presents the elemental releases as a function of time. The releases are calculated in the subsequent worksheets. See Appendix D for a description of the detailed calculations. The major elements modeled are calcium, silicon and aluminum. The worksheet also determines as a function of time the precipitates which may form from the elemental mass releases. For all buffering agents, sodium aluminum silicate and aluminum oxyhydroxide precipitates may form; however, the quantity of each precipitate as a function of time is impacted by the different pH profiles. Note that if silicon is present in much larger quantities than aluminum, i.e., silicon mass $> 2.9 \times$ aluminum mass, sodium aluminum silicate is more likely to form than aluminum oxyhydroxide. Also, calcium phosphate precipitate only forms if the flag which indicates that TSP is used as a buffering agent is selected in the "Materials Input" worksheet.

Worksheet = Releases by Material

This worksheet illustrates which material classes contribute to the total elemental releases tabulated in the "Results Table" worksheet. The elemental releases in kilograms from each containment material are

tabulated. A column chart showing the contributions from each material to the total elemental mass release is also presented.

Worksheet = Precipitate by Material

Similarly to the previous worksheet, this worksheet illustrates which material classes contribute to the precipitate mass determined in the “Results Table” worksheet. The mass of the precipitates in kilograms which form from each material source is tabulated. A column chart showing the contributions from each material to the total precipitate mass release is also presented.

This worksheet, in combination with the “Releases by Material” worksheet, has been provided to assist plants in better determining which containment materials contribute to the types and quantities of precipitate formed in order to explore potential mitigation strategies.

8.2.1 Reference

- 8.2-1 NEI 04-07, Revision 0, “Pressurized Water Reactor Sump Performance Evaluation Methodology,” December 2004.

APPENDIX A: BENCH TEST DISSOLUTION RESULTS

This appendix contains two tables. Table A-1 contains sample measured pH values as well as concentration of dissolved species determined by ICP. Table A-2 contains sample areas and masses, mass losses, and calculated dissolution rates. Runs corresponding to the design test matrix are listed with no shading, while replicate runs are shaded. The key to the column contents follows. Release rates were based on solution concentrations rather than material mass loss since the recovery of some materials from the reactor was difficult.

Variable	Units	Description
Material	none	The containment material that was tested
pHa	none	Initial pH of the simulated coolant introduced into the reactor
pHb	none	pH of the simulated coolant measured after a given reaction time
T	F	Target temperature of the reactor
Time	sec	Elapsed time between start of reaction and sampling
Al	ppm	Aluminum concentration in simulated coolant sample
Ca	ppm	Calcium concentration in simulated coolant sample
Mg	ppm	Magnesium concentration in simulated coolant sample
P	ppm	Phosphorus concentration in simulated coolant sample
S	ppm	Sulfur concentration in simulated coolant sample
Si	ppm	Silicon concentration in simulated coolant sample
Zn	ppm	Zinc concentration in simulated coolant sample
Fe	ppm	Iron concentration in simulated coolant sample
Surf. Area	cm ²	Surface area of test coupon or in the case of concrete, the particle surface area
Mat. Start Mass	g	Starting mass of material placed in the reactor
Mass Loss	g	Mass of material lost from dissolution in the reactor and handling loss
Al Rel Rate/Mass	mg/kg-min	Aluminum release rate from solution concentration change normalized to material mass (used for insulation materials)
Ca Rel Rate/Mass	mg/kg-min	Calcium release rate from solution concentration change normalized to material mass
Si Rel Rate/Mass	mg/kg-min	Silicon release rate from solution concentration change normalized to material mass
S Rel Rate/Mass	mg/kg-min	Sulfur release rate from solution concentration change normalized to material mass
Al Rel Rate/Area	mg/m ² -min	Aluminum release rate from solution concentration change normalized to material area
Fe Rel Rate/Area	mg/m ² -min	Iron release rate from solution concentration change normalized to material area
Zn Rel Rate/Area	mg/m ² -min	Zinc release rate from solution concentration change normalized to material area

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pH _a	pH _b	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
E5-1	Al Sheet	4.1	6.7	190	30	15.2	1.6	0.0	0.0	0.0	0.8	NT	NT
E5-2	Al Sheet	4.1	5.7	190	60	0.5	1.7	0.0	0.0	0.0	1.2	NT	NT
E5-3	Al Sheet	4.1	5.2	190	90	0.5	1.8	0.0	0.0	0.0	0.7	NT	NT
C5-1	Al Sheet	8	8.1	190	30	17.8	0.0	0.0	0.0	0.2	2.4	NT	NT
C5-2	Al Sheet	8	8.3	190	60	51.4	0.0	0.0	0.0	0.0	1.1	NT	NT
C5-3	Al Sheet	8	8.3	190	90	99.9	0.0	0.0	0.0	0.0	1.1	NT	NT
Q7-1	Al Sheet	8	8.1	190	30	42.0	3.2	0.1	0.0	0.8	4.6	NT	NT
Q7-2	Al Sheet	8	8.1	190	60	68.6	2.4	0.1	0.0	0.6	5.6	NT	NT
Q7-3	Al Sheet	8	8.1	190	90	116.0	2.1	0.1	0.0	0.5	3.3	NT	NT
D5-1	Al Sheet	12	10.9	190	30	607.3	0.0	0.0	0.0	0.3	1.1	NT	NT
D5-2	Al Sheet	12	11.6	190	60	914.2	0.0	0.0	0.0	0.4	6.3	NT	NT
D5-3	Al Sheet	12	11.5	190	90	1152.4	0.0	0.0	0.0	0.2	0.6	NT	NT
K7-1	Al Sheet	4.1	6.3	265	30	2.1	NT	NT	NT	NT	NT	NT	NT
K7-2	Al Sheet	4.1	6.0	265	60	3.8	NT	NT	NT	NT	NT	NT	NT
K7-3	Al Sheet	4.1	5.3	265	90	6.4	NT	NT	NT	NT	NT	NT	NT
N7-1	Al Sheet	8	8.1	265	30	211.7	2.1	0.1	0.0	1.3	12.2	NT	NT
N7-2	Al Sheet	8	8.1	265	60	413.4	1.8	0.1	0.0	0.0	9.8	NT	NT
N7-3	Al Sheet	8	8.1	265	90	569.2	1.2	0.0	0.0	0.0	8.7	NT	NT
S7-1	Al Sheet	12	11.4	265	30	16275.0	NT	NT	NT	NT	NT	NT	NT
S7-2	Al Sheet	12	11.5	265	60	29680.0	NT	NT	NT	NT	NT	NT	NT
S7-3	Al Sheet	12	11.6	265	90	13155.0	NT	NT	NT	NT	NT	NT	NT
P4-1	Blank	4.1	5.7	190	30	0.8	1.9	0.1	0.0	0.0	0.1	0.4	0.2
P4-2	Blank	4.1	5.8	190	60	0.8	0.9	0.0	0.0	0.0	0.0	0.2	0.1
P4-3	Blank	4.1	5.8	190	90	0.9	1.0	0.0	0.0	0.0	0.0	0.6	0.2
N4-1	Blank	12	12.1	265	30	13.0	1.6	0.0	0.0	0.8	28.2	NT	NT
N4-2	Blank	12	12.1	265	60	8.6	1.1	0.0	0.0	0.7	23.7	NT	NT
N4-3	Blank	12	12.1	265	90	9.0	1.2	0.0	0.0	0.6	21.2	0.0	0.7
B5-1	Calsil	4.1	6.9	190	30	1.3	194.5	0.2	0.0	42.5	186.3	NT	NT
B5-2	Calsil	4.1	6.9	190	60	1.6	214.7	0.2	0.0	31.0	190.1	NT	NT
B5-3	Calsil	4.1	6.9	190	90	1.5	212.9	0.2	0.0	26.5	188.1	NT	NT
B6-1	Calsil	4.1	6.6	190	30	2.0	160.7	0.1	0.0	23.2	163.1	NT	NT
B6-2	Calsil	4.1	6.7	190	60	2.2	203.4	0.1	0.0	14.6	187.8	NT	NT
B6-3	Calsil	4.1	6.8	190	90	2.3	236.4	0.2	0.0	13.8	215.7	NT	NT
B7-1	Calsil	4.1	6.8	190	30	1.3	132.2	0.1	0.0	33.3	125.6	NT	NT
B7-2	Calsil	4.1	6.9	190	60	1.9	229.3	0.2	0.0	51.2	239.4	NT	NT
B7-3	Calsil	4.1	6.9	190	90	1.8	227.0	0.2	0.0	38.2	231.5	NT	NT
B8-1	Calsil	4.1	6.46	190	30	1.2	108.2	0.1	0.0	12.8	100.0	NT	NT
B8-2	Calsil	4.1	6.54	190	60	2.4	138.0	0.1	0.0	16.1	132.5	NT	NT
B8-3	Calsil	4.1	6.6	190	90	2.5	162.7	0.1	0.0	16.1	150.4	NT	NT
E3-1	Calsil	4.1	6.6	190	30	2.3	138.7	0.1	0.0	11.5	120.4	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
E3-2	Calsil	4.1	6.6	190	60	2.9	136.3	0.1	0.0	9.1	113.3	NT	NT
E3-3	Calsil	4.1	6.6	190	90	2.7	137.2	0.1	0.0	7.9	108.7	NT	NT
C2-1	Calsil	8	8.1	190	30	1.4	0.0	0.0	0.0	0.0	5.7	NT	NT
C2-2	Calsil	8	8.4	190	60	1.1	74.7	0.1	0.0	27.2	158.1	NT	NT
C2-3	Calsil	8	8.5	190	90	0.9	58.5	0.1	0.0	15.7	133.7	NT	NT
R7-1	Calsil	8	8.2	190	30	2.5	33.8	0.1	0.0	43.9	280.5	NT	NT
R7-2	Calsil	8	8.2	190	60	1.5	36.9	0.1	0.0	42.2	330.8	NT	NT
R7-3	Calsil	8	8.2	190	90	1.5	38.6	0.1	0.0	42.1	377.9	NT	NT
P8-1	Calsil	12	11.6	190	30	5.9	9.6	0.0	0.1	18.8	340.2	NT	NT
P8-2	Calsil	12	11.6	190	60	6.3	7.4	0.0	0.1	12.0	305.9	NT	NT
P8-3	Calsil	12	11.5	190	90	0.7	9.5	0.0	0.1	24.9	242.4	NT	NT
K2-1	Calsil	4.1	7.0	265	30	0.8	36.6	0.1	0.0	14.4	104.9	NT	NT
K2-2	Calsil	4.1	7.9	265	60	0.7	48.4	0.0	0.0	12.1	119.5	NT	NT
K2-3	Calsil	4.1	6.8	265	90	0.8	49.3	0.1	0.0	7.3	94.4	NT	NT
H2-1	Calsil	8		265	30	1.2	10.0	0.0	0.0	7.5	106.5	NT	NT
H2-2	Calsil	8		265	60	1.1	10.5	0.0	0.0	7.8	124.1	NT	NT
H2-3	Calsil	8		265	90	1.2	11.4	0.0	0.0	7.2	129.6	NT	NT
L2-1	Calsil	8	8.1	265	30	0.6	13.6	0.0	0.0	8.6	82.1	NT	NT
L2-2	Calsil	8	8.1	265	60	1.3	19.6	0.0	0.0	14.9	130.8	NT	NT
L2-3	Calsil	8	8.1	265	90	0.9	12.5	0.0	0.0	6.8	80.4	NT	NT
M2-1	Calsil	12	10.9	265	30	1.7	1.8	0.0	0.1	31.1	243.8	NT	NT
M2-2	Calsil	12	11.0	265	60	2.6	2.0	0.0	0.1	19.3	239.3	NT	NT
M2-3	Calsil	12	11.3	265	90	5.1	2.2	0.0	0.1	10.7	231.5	NT	NT
E8-1	Concrete	4.1	6.5	190	30	7.1	439.3	0.2	0.0	7.8	33.0	NT	NT
E8-2	Concrete	4.1	6.5	190	60	1.4	484.3	0.2	0.0	7.4	36.2	NT	NT
E8-3	Concrete	4.1	6.5	190	90	1.1	424.4	0.2	0.0	6.7	29.7	NT	NT
Q1-1	Concrete	4.1	6.5	190	30	10.5	165.4	0.1	0.0	25.4	38.2	NT	NT
Q1-2	Concrete	4.1	6.5	190	60	8.7	155.8	0.1	0.0	16.5	30.2	NT	NT
Q1-3	Concrete	4.1	6.4	190	90	7.0	143.6	0.1	0.0	12.4	30.9	NT	NT
C8-1	Concrete	8	8.1	190	30	2.6	93.8	0.1	0.0	9.7	15.1	NT	NT
C8-2	Concrete	8	8.2	190	60	2.4	118.6	0.1	0.0	16.6	19.3	NT	NT
C8-3	Concrete	8	8.4	190	90	2.1	117.9	0.1	0.0	16.5	18.7	NT	NT
R1-1	Concrete	8	8.1	190	30	6.6	36.2	0.1	0.1	4.6	34.8	NT	NT
R1-2	Concrete	8	8.1	190	60	6.2	35.1	0.1	0.1	4.2	33.2	NT	NT
R1-3	Concrete	8	8.1	190	90	7.6	43.4	0.1	0.1	5.4	40.6	NT	NT
D8-1	Concrete	12	12.0	190	30	8.1	64.0	0.0	0.0	11.4	16.8	NT	NT
D8-2	Concrete	12	12.0	190	60	12.8	95.8	0.0	0.0	19.5	24.0	NT	NT
D8-3	Concrete	12	12.1	190	90	15.1	102.6	0.0	0.0	20.3	26.4	NT	NT
K5-1	Concrete	4.1	6.7	265	30	7.6	120.0	0.1	0.0	2.5	17.7	NT	NT
K5-2	Concrete	4.1	6.4	265	60	4.4	97.3	0.1	0.0	1.5	18.0	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
K5-3	Concrete	4.1	6.3	265	90	4.1	97.7	0.1	0.0	1.4	24.4	NT	NT
L5-1	Concrete	8	8.0	265	30	11.4	57.7	0.1	0.0	5.0	20.5	NT	NT
L5-2	Concrete	8	8.1	265	60	13.9	67.3	0.1	0.0	5.5	24.7	NT	NT
L5-3	Concrete	8	8.1	265	90	13.0	64.5	0.1	0.0	5.3	24.3	NT	NT
M5-1	Concrete	12	12.2	265	30	45.4	43.9	0.0	0.0	31.5	48.8	NT	NT
M5-2	Concrete	12	12.2	265	60	43.0	45.6	0.0	0.0	30.8	44.2	NT	NT
M5-3	Concrete	12	12.2	265	90	25.5	59.4	0.0	0.0	31.6	50.7	NT	NT
B3-1	Durablanket	4.1	4.46	190	30	0.7	0.0	0.0	0.0	0.0	0.3	NT	NT
B3-2	Durablanket	4.1	4.42	190	60	0.7	0.0	0.0	0.0	0.0	0.7	NT	NT
B3-3	Durablanket	4.1	4.5	190	90	0.7	0.0	0.0	0.0	0.0	0.6	NT	NT
E2-1	Durablanket	4.1	4.5	190	30	0.1	1.7	0.0	0.0	0.0	1.0	NT	NT
E2-2	Durablanket	4.1	4.5	190	60	0.0	1.7	0.0	0.0	0.0	0.9	NT	NT
E2-3	Durablanket	4.1	4.5	190	90	0.0	1.5	0.0	0.0	0.0	0.9	NT	NT
C3-1	Durablanket	8	8.1	190	30	5.2	0.0	0.0	0.0	0.0	8.0	NT	NT
C3-2	Durablanket	8	8.2	190	60	13.3	0.0	0.0	0.0	0.0	20.8	NT	NT
C3-3	Durablanket	8	8.3	190	90	17.0	0.0	0.0	0.0	0.0	28.8	NT	NT
Q4-1	Durablanket	4.1	5.1	190	30	1.1	1.5	0.1	0.0	0.3	2.8	NT	NT
Q4-2	Durablanket	4.1	4.7	190	60	1.2	1.3	0.1	0.0	0.4	1.7	NT	NT
Q4-3	Durablanket	4.1	4.7	190	90	1.5	1.4	0.1	0.0	0.3	2.4	NT	NT
R4-1	Durablanket	8	8.1	190	30	3.4	6.5	0.0	0.0	1.1	12.1	NT	NT
R4-2	Durablanket	8	8.0	190	60	5.8	7.6	0.0	0.0	1.1	8.0	NT	NT
R4-3	Durablanket	8	8.1	190	90	4.8	6.1	0.0	0.0	0.8	6.3	0.0	0.0
D3-1	Durablanket	12	12.0	190	30	4.3	0.0	0.0	0.0	0.1	9.6	NT	NT
D3-2	Durablanket	12	12.0	190	60	17.8	0.0	0.0	0.0	0.3	43.6	NT	NT
D3-3	Durablanket	12	12.0	190	90	24.1	0.0	0.0	0.0	0.3	59.7	NT	NT
K1-1	Durablanket	4.1	6.3	265	30	2.0	5.2	0.0	0.0	0.0	6.6	NT	NT
K1-2	Durablanket	4.1	5.4	265	60	1.7	6.2	0.0	0.0	0.0	8.1	NT	NT
K1-3	Durablanket	4.1	5.9	265	90	1.4	4.2	0.0	0.0	0.0	5.9	NT	NT
O4-1	Durablanket	4.1	5.4	265	30	2.6	2.4	0.1	0.0	0.0	9.0	NT	NT
O4-2	Durablanket	4.1	5.9	265	60	3.1	1.5	0.1	0.0	0.0	8.7	NT	NT
O4-3	Durablanket	4.1	5.4	265	90	4.0	1.1	0.1	0.0	0.0	10.7	NT	NT
L1-1	Durablanket	8	8.0	265	30	6.8	1.1	0.0	0.0	0.0	8.2	NT	NT
L1-2	Durablanket	8	8.1	265	60	14.6	1.2	0.0	0.0	0.0	19.1	NT	NT
L1-3	Durablanket	8	8.0	265	90	25.2	1.6	0.0	0.0	0.0	32.8	NT	NT
M1-1	Durablanket	12	12.0	265	30	29.1	0.5	0.0	0.0	0.2	38.5	NT	NT
M1-2	Durablanket	12	12.0	265	60	21.4	0.4	0.0	0.0	0.3	27.0	NT	NT
M1-3	Durablanket	12	12.0	265	90	38.2	0.4	0.0	0.0	0.3	71.3	NT	NT
E6-1	Fiberglass	4.1	5.8	190	30	0.3	4.0	0.1	0.0	2.2	5.4	NT	NT
E6-2	Fiberglass	4.1	5.2	190	60	0.0	2.2	0.0	0.0	1.1	0.9	NT	NT
E6-3	Fiberglass	4.1	5.3	190	90	0.0	3.1	0.1	0.0	1.1	1.2	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
Q3-1	Fiberglass	4.1	5.4	190	30	1.0	2.4	0.1	0.0	6.1	4.8	NT	NT
Q3-2	Fiberglass	4.1	5.4	190	60	0.9	2.3	0.1	0.0	4.9	5.2	NT	NT
Q3-3	Fiberglass	4.1	5.4	190	90	1.1	2.6	0.2	0.0	4.2	6.4	NT	NT
C6-1	Fiberglass	8	8.1	190	30	1.0	0.5	0.1	0.0	5.0	9.1	NT	NT
C6-2	Fiberglass	8	8.2	190	60	1.2	1.0	0.1	0.0	5.2	20.4	NT	NT
C6-3	Fiberglass	8	8.3	190	90	1.5	2.7	0.2	0.0	5.5	36.0	NT	NT
R3-1	Fiberglass	8	8.1	190	30	4.2	6.0	0.1	0.0	8.8	14.1	NT	NT
R3-2	Fiberglass	8	8.1	190	60	4.0	7.4	0.1	0.0	8.9	27.1	NT	NT
R3-3	Fiberglass	8	8.1	190	90	3.9	7.6	0.1	0.0	7.1	39.3	NT	NT
D6-1	Fiberglass	12	11.9	190	30	2.5	6.8	0.0	0.0	2.6	74.3	NT	NT
D6-2	Fiberglass	12	12.0	190	60	4.0	17.6	0.0	0.0	2.9	171.2	NT	NT
D6-3	Fiberglass	12	12.0	190	90	4.9	24.8	0.0	0.0	3.4	233.3	NT	NT
K4-1	Fiberglass	4.1	6.4	265	30	4.2	9.1	0.1	0.0	1.2	33.7	NT	NT
K4-2	Fiberglass	4.1	6.1	265	60	2.4	14.3	0.3	0.0	0.6	75.0	NT	NT
K4-3	Fiberglass	4.1	6.2	265	90	1.7	19.8	0.4	0.0	0.4	110.0	NT	NT
L4-1	Fiberglass	8	8.0	265	30	2.7	4.8	0.2	0.0	2.7	42.2	NT	NT
L4-2	Fiberglass	8	8.1	265	60	3.2	8.2	0.2	0.0	2.5	61.2	NT	NT
L4-3	Fiberglass	8	8.1	265	90	3.8	11.2	0.2	0.0	2.4	85.5	NT	NT
M4-1	Fiberglass	12	12.0	265	30	6.7	9.7	0.0	0.0	5.9	171.0	NT	NT
M4-2	Fiberglass	12	12.0	265	60	8.3	13.6	0.0	0.0	4.5	214.9	NT	NT
M4-3	Fiberglass	12	12.0	265	90	8.6	7.1	0.0	0.0	3.7	222.7	NT	NT
P2-1	Galvanized	4.1	5.9	190	30	NT	NT	NT	NT	NT	NT	2.9	0.8
P2-2	Galvanized	4.1	5.8	190	60	NT	NT	NT	NT	NT	NT	4.9	1.0
P2-3	Galvanized	4.1	5.8	190	90	NT	NT	NT	NT	NT	NT	6.9	1.1
Q6-1	Galvanized	8	8.1	190	30	NT	NT	NT	NT	NT	NT	0.0	0.0
Q6-2	Galvanized	8	8.1	190	60	NT	NT	NT	NT	NT	NT	0.0	0.0
Q6-3	Galvanized	8	8.1	190	90	NT	NT	NT	NT	NT	NT	0.1	0.0
P6-1	Galvanized	12	12.0	190	30	NT	NT	NT	NT	NT	NT	2.3	0.0
P6-2	Galvanized	12	12.0	190	60	NT	NT	NT	NT	NT	NT	3.2	0.0
P6-3	Galvanized	12	12.1	190	90	NT	NT	NT	NT	NT	NT	4.5	0.2
O2-1	Galvanized	4.1	5.4	265	30	NT	NT	NT	NT	NT	NT	1.0	0.8
O2-2	Galvanized	4.1	5.4	265	60	NT	NT	NT	NT	NT	NT	1.9	0.1
O2-3	Galvanized	4.1	5.5	265	90	NT	NT	NT	NT	NT	NT	0.0	0.0
N6-1	Galvanized	8	8.1	265	30	NT	NT	NT	NT	NT	NT	0.0	0.0
N6-2	Galvanized	8	8.2	265	60	NT	NT	NT	NT	NT	NT	0.0	0.0
N6-3	Galvanized	8	8.1	265	90	NT	NT	NT	NT	NT	NT	0.1	0.0
N2-1	Galvanized	12	12.1	265	30	NT	NT	NT	NT	NT	NT	7.1	0.7
N2-2	Galvanized	12	12.1	265	60	NT	NT	NT	NT	NT	NT	12.4	0.7
N2-3	Galvanized	12	12.1	265	90	NT	NT	NT	NT	NT	NT	15.2	0.4
P3-1	Interam	4.1	4.8	190	30	0.7	1.1	0.0	0.0	0.0	0.0	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
P3-2	Interam	4.1	4.7	190	60	0.7	0.6	0.0	0.0	0.0	0.0	NT	NT
P3-3	Interam	4.1	4.7	190	90	0.7	0.6	0.0	0.0	0.0	0.0	NT	NT
Q8-1	Interam	8	8.1	190	30	8.1	6.2	0.1	0.0	0.9	8.1	NT	NT
Q8-2	Interam	8	8.1	190	60	10.5	2.9	0.1	0.0	0.7	6.3	NT	NT
Q8-3	Interam	8	8.1	190	90	7.6	3.3	0.0	0.0	0.7	4.8	NT	NT
P7-1	Interam	12	12.0	190	30	161.1	3.1	0.0	0.0	0.6	22.3	NT	NT
P7-2	Interam	12	12.0	190	60	61.4	3.0	0.0	0.0	0.9	17.2	NT	NT
P7-3	Interam	12	12.0	190	90	83.5	2.5	0.0	0.0	0.5	12.2	NT	NT
O3-1	Interam	4.1	5.4	265	30	1.0	1.3	0.1	0.1	0.0	4.0	NT	NT
O3-2	Interam	4.1	5.5	265	60	1.0	0.9	0.1	0.1	0.0	3.1	NT	NT
O3-3	Interam	4.1	5.5	265	90	1.2	0.8	0.1	0.1	0.0	3.3	NT	NT
N8-1	Interam	8	8.1	265	30	5.4	2.9	0.1	0.1	0.5	5.1	NT	NT
N8-2	Interam	8	8.1	265	60	10.1	2.9	0.0	0.1	0.5	5.9	NT	NT
N8-3	Interam	8	8.1	265	90	11.9	2.5	0.0	0.1	0.4	5.0	NT	NT
N3-1	Interam	12	12.1	265	30	35.6	0.4	0.0	0.1	0.3	16.6	NT	NT
N3-2	Interam	12	12.1	265	60	50.6	0.5	0.0	0.1	0.4	23.1	NT	NT
N3-3	Interam	12	12.1	265	90	50.5	0.6	0.0	0.1	0.7	22.7	NT	NT
B4-1	Mineral Wool	4.1	4.6	190	30	0.7	0.0	0.0	0.0	0.0	0.7	NT	NT
B4-2	Mineral Wool	4.1	4.6	190	60	0.7	0.0	0.1	0.0	0.0	1.0	NT	NT
B4-3	Mineral Wool	4.1	4.6	190	90	0.7	0.0	0.1	0.0	0.0	1.0	NT	NT
E4-1	Mineral Wool	4.1	5.7	190	30	0.0	5.5	0.0	0.0	0.0	2.3	NT	NT
E4-2	Mineral Wool	4.1	4.9	190	60	0.0	1.8	0.0	0.0	0.0	1.0	NT	NT
E4-3	Mineral Wool	4.1	4.8	190	90	0.0	1.4	0.0	0.0	0.0	0.8	NT	NT
C4-1	Mineral Wool	8	8.1	190	30	0.9	0.0	0.1	0.0	0.2	2.6	NT	NT
C4-2	Mineral Wool	8	8.3	190	60	1.0	0.0	0.1	0.0	0.1	4.1	NT	NT
C4-3	Mineral Wool	8	8.4	190	90	1.5	0.0	0.2	0.0	0.1	7.4	NT	NT
R6-1	Mineral Wool	8	8.1	190	30	4.3	10.1	0.1	0.0	2.2	8.2	NT	NT
R6-2	Mineral Wool	8	8.1	190	60	5.2	11.3	0.1	0.0	2.3	11.4	NT	NT
R6-3	Mineral	8	8.1	190	90	4.7	10.2	0.1	0.0	1.8	10.5	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
	Wool												
D4-1	Mineral Wool	12	12.0	190	30	2.1	2.9	0.0	0.0	0.2	11.4	NT	NT
D4-2	Mineral Wool	12	12.0	190	60	5.1	9.9	0.0	0.0	0.5	32.2	NT	NT
D4-3	Mineral Wool	12	12.0	190	90	7.4	19.3	0.0	0.0	0.6	47.2	NT	NT
K3-1	Mineral Wool	4.1	6.1	265	30	1.3	4.3	0.1	0.0	0.0	4.5	NT	NT
K3-2	Mineral Wool	4.1	5.6	265	60	1.1	6.3	0.1	0.0	0.0	5.3	NT	NT
K3-3	Mineral Wool	4.1	5.7	265	90	2.0	12.0	0.2	0.0	0.0	9.4	NT	NT
H4-1	Mineral Wool	8		265	30	3.1	3.9	0.2	0.0	0.0	10.9	NT	NT
H4-2	Mineral Wool	8		265	60	5.7	7.8	0.3	0.0	0.0	20.1	NT	NT
H4-3	Mineral Wool	8		265	90	5.9	8.7	0.3	0.0	0.0	21.0	NT	NT
L3-1	Mineral Wool	8	8.0	265	30	4.8	13.8	0.2	0.0	0.0	17.3	NT	NT
L3-2	Mineral Wool	8	8.1	265	60	5.4	16.6	0.2	0.0	0.0	19.7	NT	NT
L3-3	Mineral Wool	8	8.0	265	90	4.6	14.6	0.2	0.0	0.0	16.7	NT	NT
M3-1	Mineral Wool	12	12.0	265	30	4.7	1.8	0.0	0.0	0.7	56.8	NT	NT
M3-2	Mineral Wool	12	12.1	265	60	12.0	15.2	0.0	0.0	0.8	67.6	NT	NT
M3-3	Mineral Wool	12	12.1	265	90	10.6	14.5	0.0	0.0	0.5	62.8	NT	NT
E7-1	Min-K	4.1	5.8	190	30	0.0	1.6	0.0	0.0	0.0	2.7	NT	NT
E7-2	Min-K	4.1	4.5	190	60	0.0	1.5	0.0	0.0	0.0	1.0	NT	NT
E7-3	Min-K	4.1	4.5	190	90	0.0	1.3	0.0	0.0	0.0	1.9	NT	NT
Q2-1	MIN-K	4.1	5.0	190	30	1.0	1.9	0.1	0.0	0.3	14.0	NT	NT
Q2-2	MIN-K	4.1	4.9	190	60	0.9	1.2	0.1	0.0	0.4	11.7	NT	NT
Q2-3	MIN-K	4.1	4.9	190	90	1.2	1.7	0.1	0.0	0.4	10.1	NT	NT
C7-1	Min-K	8	8.1	190	30	0.9	0.3	0.0	0.0	0.5	66.4	NT	NT
C7-2	Min-K	8	8.2	190	60	0.9	0.0	0.0	0.0	0.4	125.3	NT	NT
C7-3	Min-K	8	8.1	190	90	0.9	0.0	0.0	0.0	0.3	157.0	NT	NT
R2-1	MIN-K	8	8.0	190	30	1.9	4.5	0.1	0.0	0.6	97.6	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
R2-2	MIN-K	8	8.0	190	60	1.9	3.6	0.0	0.0	0.5	156.8	NT	NT
R2-3	MIN-K	8	8.0	190	90	2.7	6.2	0.1	0.1	1.0	217.8	NT	NT
D7-1	Min-K	12	12.0	190	30	0.9	0.0	0.0	0.0	0.6	97.9	NT	NT
D7-2	Min-K	12	12.0	190	60	0.9	0.0	0.0	0.0	0.7	120.4	NT	NT
D7-3	Min-K	12	11.9	190	90	1.0	0.0	0.0	0.0	0.9	141.9	NT	NT
K8-1	Min-K	4.1	6.2	265	30	7.4	3.5	0.1	0.0	0.1	33.7	NT	NT
K8-2	Min-K	4.1	5.8	265	60	2.8	1.9	0.1	0.0	0.0	35.5	NT	NT
K8-3	Min-K	4.1	5.3	265	90	0.9	1.7	0.0	0.0	0.0	52.2	NT	NT
L8-1	Min-K	8	8.0	265	30	1.1	2.5	0.0	0.0	0.0	39.7	NT	NT
L8-2	Min-K	8	8.0	265	60	2.9	2.9	0.0	0.0	0.0	66.8	NT	NT
L8-3	Min-K	8	8.1	265	90	1.9	2.4	0.0	0.0	0.0	40.8	NT	NT
M8-1	MIN-K	12	12.1	265	30	1.8	0.8	0.0	0.0	0.5	135.4	NT	NT
M8-2	Min-K	12	12.0	265	60	7.9	1.1	0.0	0.0	0.5	121.0	NT	NT
M8-3	Min-K	12	12.1	265	90	16.6	1.8	0.0	0.0	0.6	99.8	NT	NT
B1-1	Nukon	4.1	5.3	190	30	0.7	0.0	0.7	0.0	2.1	0.9	NT	NT
B1-2	Nukon	4.1	5.4	190	60	0.7	0.0	0.1	0.0	0.9	1.5	NT	NT
B1-3	Nukon	4.1	5.5	190	90	0.7	0.0	0.1	0.0	1.8	2.8	NT	NT
E1-1	Nukon	4.1	5.3	190	30	0.2	3.0	0.1	0.0	1.4	2.7	NT	NT
E1-2	Nukon	4.1	5.4	190	60	0.1	2.5	0.1	0.0	1.5	2.5	NT	NT
E1-3	Nukon	4.1	5.4	190	90	0.0	2.4	0.1	0.0	1.2	2.4	NT	NT
C1-1	Nukon	8	8.1	190	30	0.7	0.0	0.1	0.0	2.0	6.4	NT	NT
C1-2	Nukon	8	8.4	190	60	0.6	0.0	0.0	0.0	0.0	1.5	NT	NT
C1-3	Nukon	8	8.3	190	90	1.0	0.0	0.2	0.0	1.8	19.8	NT	NT
R5-1	Nukon	8	8.1	190	30	4.1	9.7	0.1	0.1	7.0	23.5	NT	NT
R5-2	Nukon	8	8.1	190	60	11.8	10.1	0.1	0.2	6.4	32.4	NT	NT
R5-2	Nukon	8	8.1	190	90	4.9	10.8	0.2	0.0	6.1	46.8	NT	NT
D1-1	Nukon	12	11.91	190	30	0.8	0.0	0.1	0.0	0.4	10.8	NT	NT
D1-2	Nukon	12	11.94	190	60	0.8	0.0	0.0	0.0	0.0	8.3	NT	NT
D1-3	Nukon	12	11.91	190	90	0.7	0.0	0.0	0.0	0.0	4.1	NT	NT
K6-1	Nukon	4.1	6.5	265	30	2.2	5.7	0.1	0.0	0.0	18.0	NT	NT
K6-2	Nukon	4.1	6.0	265	60	0.9	6.7	0.1	0.0	0.0	20.3	NT	NT
K6-3	Nukon	4.1	5.9	265	90	1.0	8.3	0.1	0.0	0.0	30.8	NT	NT
L6-1	Nukon	8	8.0	265	30	2.7	8.3	0.2	0.0	1.2	49.6	NT	NT
L6-2	Nukon	8	8.1	265	60	3.7	17.4	0.2	0.0	1.0	67.0	NT	NT
L6-3	Nukon	8	8.1	265	90	3.8	10.8	0.2	0.0	0.7	68.0	NT	NT
M6-1	Nukon	12	12.0	265	30	10.1	16.0	0.0	0.0	4.4	206.1	NT	NT
M6-2	Nukon	12	12.0	265	60	7.0	10.4	0.0	0.0	2.3	144.0	NT	NT
M6-3	Nukon	12	12.0	265	90	8.1	8.5	0.0	0.0	1.5	191.9	NT	NT
P1-1	Steel	4.1	5.0	190	30	NT	NT	NT	NT	NT	NT	1.8	2.1
P1-2	Steel	4.1	6.2	190	60	NT	NT	NT	NT	NT	NT	1.2	9.3

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pH _a	pH _b	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
P1-3	Steel	4.1	5.3	190	90	NT	NT	NT	NT	NT	NT	1.1	19.7
Q5-1	Steel	8	8.1	190	30	NT	NT	NT	NT	NT	NT	0.0	0.0
Q5-2	Steel	8	8.0	190	60	NT	NT	NT	NT	NT	NT	0.0	0.0
Q5-3	Steel	8	8.0	190	90	NT	NT	NT	NT	NT	NT	0.0	0.0
P5-1	Steel	12	12.0	190	30	NT	NT	NT	NT	NT	NT	0.0	0.1
P5-2	Steel	12	12.0	190	60	NT	NT	NT	NT	NT	NT	0.0	0.0
P5-3	Steel	12	12.1	190	90	NT	NT	NT	NT	NT	NT	0.1	0.1
O1-1	Steel	4.1	5.2	265	30	NT	NT	NT	NT	NT	NT	0.0	0.3
O1-2	Steel	4.1	5.4	265	60	NT	NT	NT	NT	NT	NT	0.0	3.2
O1-3	Steel	4.1	5.7	265	90	NT	NT	NT	NT	NT	NT	0.0	4.5
N5-1	Steel	8	8.0	265	30	NT	NT	NT	NT	NT	NT	NT	0.0
N5-2	Steel	8	8.1	265	60	NT	NT	NT	NT	NT	NT	NT	0.0
N5-3	Steel	8	8.1	265	90	NT	NT	NT	NT	NT	NT	NT	1.1
N1-1	Steel	12	12.1	265	30	NT	NT	NT	NT	NT	NT	NT	0.5
N1-2	Steel	12	12.1	265	60	NT	NT	NT	NT	NT	NT	NT	0.6
N1-3	Steel	12	12.1	265	90	NT	NT	NT	NT	NT	NT	NT	0.6

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _a	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² -min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² -min	Zn Rel Rate / Area mg/m ² -min
E5-1	Al Sheet	4.1	190	30	17.8	1.855	0.0021		37.2	3.6	1.9	0.0		
E5-2	Al Sheet	4.1	190	60	17.8				-31.7	0.4	0.7	0.0		
E5-3	Al Sheet	4.1	190	90	17.8				0.0	0.1	-0.9	0.0		
C5-1	Al Sheet	8	190	30	17.8	1.848	-0.0012		30.8	0.0	4.0	0.3		
C5-2	Al Sheet	8	190	60	17.8				48.2	0.0	-1.8	-0.2		
C5-3	Al Sheet	8	190	90	17.8				55.1	0.0	0.0	0.0		
Q7-1	Al Sheet	8	190	30	25.7	2.4662	0.0128		85.8	6.9	9.8	1.7		
Q7-2	Al Sheet	8	190	60	25.7				48.7	-1.6	1.9	-0.3		
Q7-3	Al Sheet	8	190	90	25.7				77.2	-0.6	-4.0	-0.1		
D5-1	Al Sheet	12	190	30	17.8	1.8569	0.2769		559.6	0.0	1.0	0.3		
D5-2	Al Sheet	12	190	60	17.8				189.0	0.0	3.1	0.1		
D5-3	Al Sheet	12	190	90	17.8				73.1	0.0	-1.7	-0.1		
K7-1	Al Sheet	4.1	265	30	25.7	2.595	0.0405		4.3					
K7-2	Al Sheet	4.1	265	60	25.7				3.3					
K7-3	Al Sheet	4.1	265	90	25.7				4.4					
N7-1	Al Sheet	8	265	30	25.7	1.8651	0.106		411.7	5.7	32.7	3.4		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _i	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² - min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² - min	Zn Rel Rate / Area mg/m ² - min
N7-2	Al Sheet	8	265	60	25.7				348.7	-0.9	-5.7	-2.9		
N7-3	Al Sheet	8	265	90	25.7				235.6	-1.2	-2.3	0.0		
S7-1	Al Sheet	12	265	30	25.7	2.68	0.7884		17782.1					
S7-2	Al Sheet	12	265	60	25.7				11705.6					
S7-3	Al Sheet	12	265	90	25.7				-10824.1					
P4-1	Blank	4.1	190	30										
P4-2	Blank	4.1	190	60										
P4-3	Blank	4.1	190	90										
N4-1	Blank	12	265	30		0	1.2E-16							
N4-2	Blank	12	265	60										
N4-3	Blank	12	265	90										
B5-1	Calsil	4.1	190	30	4E+05	4.09	0.2025	0.96		144.5	138.4	31.6		
B5-2	Calsil	4.1	190	60				0.17		12.5	2.4	-7.1		
B5-3	Calsil	4.1	190	90				-0.03		-0.9	-1.0	-2.3		
B6-1	Calsil	4.1	190	30		4.188	0.1733	1.36		111.3	113.0	16.0		
B6-2	Calsil	4.1	190	60				0.14		23.4	13.5	-4.7		
B6-3	Calsil	4.1	190	90				0.04		13.0	11.0	-0.3		
B7-1	Calsil	4.1	190	30		4.178	0.1471	1.00		98.9	94.0	24.9		
B7-2	Calsil	4.1	190	60				0.37		59.9	70.2	11.1		
B7-3	Calsil	4.1	190	90				-0.05		-1.1	-3.8	-6.3		
B8-1	Calsil	4.1	190	30		2.079	0.0985	1.87		165.3	152.8	19.5		
B8-2	Calsil	4.1	190	60				1.52		38.2	41.7	4.3		
B8-3	Calsil	4.1	190	90				0.08		25.7	18.7	-0.1		
E3-1	Calsil	4.1	190	30		4.185	0.1592	2.23		133.4	115.8	11.0		
E3-2	Calsil	4.1	190	60				0.48		-2.1	-6.1	-2.0		
E3-3	Calsil	4.1	190	90				-0.11		0.7	-3.3	-0.9		
C2-1	Calsil	8	190	30		4.181	0.0936	0.90		0.0	3.7	0.0		
C2-2	Calsil	8	190	60				-0.15		37.9	77.4	13.8		
C2-3	Calsil	8	190	90				-0.07		-6.1	-9.1	-4.3		
R7-1	Calsil	8	190	30		6.0604	-1.6229	1.47		19.5	162.1	25.4		
R7-2	Calsil	8	190	60				-0.50		1.5	24.5	-0.9		
R7-3	Calsil	8	190	90				0.00		0.7	18.7	0.0		
P8-1	Calsil	12	190	30		6.0599	-0.0423	3.57		5.8	204.8	11.3		
P8-2	Calsil	12	190	60				0.19		-1.1	-17.5	-3.5		
P8-3	Calsil	12	190	90				-2.35		0.9	-26.6	5.4		
K2-1	Calsil	4.1	265	30		6.0607	0.3808	0.50		23.9	68.7	9.4		
K2-2	Calsil	4.1	265	60				-0.02		6.7	8.3	-1.3		
K2-3	Calsil	4.1	265	90				0.02		0.5	-11.9	-2.3		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _s	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² -min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² -min	Zn Rel Rate / Area mg/m ² -min
H2-1	Calsil	8	265	30		6.0604	0.2893	0.82		6.8	72.7	5.1		
H2-2	Calsil	8	265	60				-0.03		0.3	10.4	0.1		
H2-3	Calsil	8	265	90				0.00		0.5	2.8	-0.3		
L2-1	Calsil	8	265	30		6.0635	0.4751	0.40		8.6	51.7	5.4		
L2-2	Calsil	8	265	60				0.34		3.2	26.2	3.4		
L2-3	Calsil	8	265	90				-0.17		-3.2	-22.5	-3.6		
M2-1	Calsil	12	265	30		6.0603	-0.5981	1.11		1.2	158.7	20.2		
M2-2	Calsil	12	265	60				0.51		0.1	-2.5	-6.6		
M2-3	Calsil	12	265	90				1.17		0.1	-3.7	-4.0		
E8-1	Concrete	4.1	190	30	4E+05	4.009	0.1675	6.70		416.5	31.3	7.4		
E8-2	Concrete	4.1	190	60				-4.97		39.4	2.8	-0.3		
E8-3	Concrete	4.1	190	90				-0.23		-47.3	-5.1	-0.6		
Q1-1	Concrete	4.1	190	30	5E+05	5.8005	1.0765	7.78		122.5	28.3	18.8		
Q1-2	Concrete	4.1	190	60				-1.18		-6.2	-5.1	-5.8		
Q1-3	Concrete	4.1	190	90				-0.91		-6.7	0.4	-2.3		
C8-1	Concrete	8	190	30		4.01		1.81		65.2	10.5	6.7		
C8-2	Concrete	8	190	60				-0.15		15.0	2.6	4.2		
C8-3	Concrete	8	190	90				-0.10		-0.3	-0.3	0.0		
R1-1	Concrete	8	190	30	5E+05	5.7998	0.3293	3.95		21.6	20.8	2.7		
R1-2	Concrete	8	190	60				-0.20		-0.6	-0.8	-0.2		
R1-3	Concrete	8	190	90				0.56		3.4	3.0	0.5		
D8-1	Concrete	12	190	30	4E+05	4.0515	0.2272	3.03		23.8	6.3	4.2		
D8-2	Concrete	12	190	60				1.20		8.2	1.8	2.1		
D8-3	Concrete	12	190	90				0.30		0.9	0.3	0.1		
K5-1	Concrete	4.1	265	30	5E+05	5.8013	0.2811	5.24		83.2	12.3	1.7		
K5-2	Concrete	4.1	265	60				-1.86		-13.6	0.1	-0.6		
K5-3	Concrete	4.1	265	90				-0.19		0.2	3.2	-0.1		
L5-1	Concrete	8	265	30	5E+05	5.7998	0.4084	8.63		43.6	15.5	3.8		
L5-2	Concrete	8	265	60				1.61		6.3	2.8	0.3		
L5-3	Concrete	8	265	90				-0.48		-1.6	-0.2	-0.1		
M5-1	Concrete	12	265	30	5E+05	5.799	0.6977	31.95		30.9	34.3	22.2		
M5-2	Concrete	12	265	60				-1.46		1.1	-2.8	-0.4		
M5-3	Concrete	12	265	90				-8.96		7.1	3.4	0.4		
B3-1	Durablanket	4.1	190	30		0.412	-0.0032	4.20		0.0	2.1	0.0		
B3-2	Durablanket	4.1	190	60				0.29		0.0	1.6	0.0		
B3-3	Durablanket	4.1	190	90				-0.07		0.0	0.0	0.0		
E2-1	Durablanket	4.1	190	30		0.413	0.0131	1.26		18.3	10.6	0.1		
E2-2	Durablanket	4.1	190	60				-1.05		-0.7	-0.7	-0.1		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _a	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² - min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² - min	Zn Rel Rate / Area mg/m ² - min
E2-3	Durablanket	4.1	190	90				0.22		-1.3	-0.5	0.0		
C3-1	Durablanket	8	190	30		0.411	-3.7581	24.47		0.0	37.5	0.0		
C3-2	Durablanket	8	190	60				26.55		0.0	42.3	0.0		
C3-3	Durablanket	8	190	90				7.05		0.0	15.0	0.0		
Q4-1	Durablanket	8	190	30		0.5943	0.008	8.16		10.8	20.1	2.4		
Q4-2	Durablanket	8	190	60				0.55		-1.4	-7.2	0.6		
Q4-3	Durablanket	8	190	90				1.47		0.6	4.0	-0.8		
R4-1	Durablanket	8	190	30		0.5941	0.0013	19.51		36.7	68.6	6.5		
R4-2	Durablanket	8	190	60				11.31		5.3	-19.4	-0.2		
R4-3	Durablanket	8	190	90				-3.94		-5.7	-6.6	-1.2		
D3-1	Durablanket	12	190	30		0.41	-0.0395	41.32		0.0	91.7	0.6		
D3-2	Durablanket	12	190	60				107.74		0.0	271.7	2.2		
D3-3	Durablanket	12	190	90				40.74		0.0	103.7	-0.4		
K1-1	Durablanket	4.1	265	30		0.5937	0.0084	17.15		43.7	54.9	0.0		
K1-2	Durablanket	4.1	265	60				-2.90		7.6	11.9	0.0		
K1-3	Durablanket	4.1	265	90				-1.57		-13.5	-14.5	0.0		
O4-1	Durablanket	4.1	265	30		0.5948	-0.0011	21.21		20.0	74.2	0.0		
O4-2	Durablanket	4.1	265	60				4.06		-6.8	-2.0	0.0		
O4-3	Durablanket	4.1	265	90				5.54		-2.4	12.3	0.0		
L1-1	Durablanket	8	265	30		0.5943	0.0273	50.91		8.3	62.1	0.0		
L1-2	Durablanket	8	265	60				51.77		0.5	71.5	0.0		
L1-3	Durablanket	8	265	90				59.99		2.1	77.8	0.2		
M1-1	Durablanket	12	265	30		0.5942	0.0798	232.45		3.8	307.4	1.5		
M1-2	Durablanket	12	265	60				-54.92		-0.8	-81.8	1.0		
M1-3	Durablanket	12	265	90				103.25		0.5	271.8	0.0		
E6-1	Fiberglass	4.1	190	30		0.905	-0.0125	1.18		19.0	25.3	10.1		
E6-2	Fiberglass	4.1	190	60				-1.07		-7.7	-19.2	-4.5		
E6-3	Fiberglass	4.1	190	90				0.00		3.2	1.0	-0.1		
Q3-1	Fiberglass	4.1	190	30		1.3001	0.0137	3.29		7.8	15.7	20.1		
Q3-2	Fiberglass	4.1	190	60				-0.22		-0.2	1.3	-3.5		
Q3-3	Fiberglass	4.1	190	90				0.44		0.9	3.0	-1.5		
C6-1	Fiberglass	8	190	30		0.901	0.0023	3.02		1.3	26.3	14.6		
C6-2	Fiberglass	8	190	60				0.29		1.2	26.0	0.5		
C6-3	Fiberglass	8	190	90				0.51		2.9	26.6	0.4		
R3-1	Fiberglass	8	190	30		1.3007	0.0147	11.14		16.0	37.6	23.4		
R3-2	Fiberglass	8	190	60				-0.39		3.2	29.3	0.4		
R3-3	Fiberglass	8	190	90				-0.23		0.3	22.3	-3.4		
D6-1	Fiberglass	12	190	30		0.899	0.0497	10.97		29.4	320.3	11.1		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _i	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² -min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² -min	Zn Rel Rate / Area mg/m ² -min
D6-2	Fiberglass	12	190	60				5.30		39.3	351.8	1.2		
D6-3	Fiberglass	12	190	90				2.50		21.0	182.0	1.4		
K4-1	Fiberglass	4.1	265	30		1.3	0.0613	13.01		28.5	105.5	3.7		
K4-2	Fiberglass	4.1	265	60				-4.85		14.1	112.2	-1.7		
K4-3	Fiberglass	4.1	265	90				-1.63		12.5	80.1	-0.3		
L4-1	Fiberglass	8	265	30		1.2997	0.0534	8.22		14.6	129.4	8.2		
L4-2	Fiberglass	8	265	60				1.49		8.9	50.2	-0.5		
L4-3	Fiberglass	8	265	90				1.14		6.8	53.7	-0.2		
M4-1	Fiberglass	12	265	30		1.2998	0.1882	23.87		34.6	612.4	21.0		
M4-2	Fiberglass	12	265	60				5.06		12.4	138.6	-4.2		
M4-3	Fiberglass	12	265	90				0.91		-17.6	21.3	-2.3		
P2-1	Galvanized	4.1	190	30	91.2	13.9354	0.0114							1.3
P2-2	Galvanized	4.1	190	60	91.2									0.7
P2-3	Galvanized	4.1	190	90	91.2									0.6
Q6-1	Galvanized	8	190	30	91.2	14.0768	0.0083							0.0
Q6-2	Galvanized	8	190	60	91.2									0.0
Q6-3	Galvanized	8	190	90	91.2									0.0
P6-1	Galvanized	12	190	30	91.2	14.2719	0.0013							1.0
P6-2	Galvanized	12	190	60	91.2									0.3
P6-3	Galvanized	12	190	90	91.2									0.4
O2-1	Galvanized	4.1	265	30	91.2	13.8539	0.0077							0.5
O2-2	Galvanized	4.1	265	60	91.2									0.5
O2-3	Galvanized	4.1	265	90	91.2									-0.8
N6-1	Galvanized	8	265	30	91.2	14.0797	0.0006							0.0
N6-2	Galvanized	8	265	60	91.2									0.0
N6-3	Galvanized	8	265	90	91.2									0.0
N2-1	Galvanized	12	265	30	91.2	14.1467	0.0045							3.8
N2-2	Galvanized	12	265	60	91.2									2.5
N2-3	Galvanized	12	265	90	91.2									1.1
P3-1	Interam	4.1	190	30		0.0394	-0.002	63.99		99.0	0.0	0.0		
P3-2	Interam	4.1	190	60				3.99		-35.1	0.0	0.0		
P3-3	Interam	4.1	190	90				-1.29		1.4	0.0	0.0		
Q8-1	Interam	8	190	30		0.0389	0.0087	1074.9		833.5	1076.6	123.5		
Q8-2	Interam	8	190	60				292.30		-401.1	-214.8	-25.4		
Q8-3	Interam	8	190	90				-307.21		42.1	-153.4	-3.1		
P7-1	Interam	12	190	30		0.039	0.0287	17396.6		339.0	2405.9	64.5		
P7-2	Interam	12	190	60				-9348.8		-11.6	-476.3	31.2		
P7-3	Interam	12	190	90				1762.23		-40.3	-400.1	-37.5		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _i	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² - min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² - min	Zn Rel Rate / Area mg/m ² - min
O3-1	Interam	4.1	265	30		0.0392	-0.0002	130.78		173.1	519.0	0.0		
O3-2	Interam	4.1	265	60				1.64		-54.9	-104.6	0.0		
O3-3	Interam	4.1	265	90				22.48		-3.6	27.1	0.0		
N8-1	Interam	8	265	30		0.039	0.0082	696.40		370.0	656.4	67.8		
N8-2	Interam	8	265	60				526.90		-2.2	86.1	-5.4		
N8-3	Interam	8	265	90				187.46		-39.2	-89.2	-12.7		
N3-1	Interam	12	265	30		0.0391	0.0243	4567.2		56.1	2121.5	40.6		
N3-2	Interam	12	265	60				1709.4		6.0	747.1	11.6		
N3-3	Interam	12	265	90				-10.95		8.0	-43.8	28.5		
B4-1	Mineral Wool	4.1	190	30		0.639	0.0198	3.88		0.0	3.6	0.0		
B4-2	Mineral Wool	4.1	190	60				0.10		0.0	1.3	0.0		
B4-3	Mineral Wool	4.1	190	90				-0.06		0.0	0.0	0.0		
E4-1	Mineral Wool	4.1	190	30		0.641	0.0172	0.00		36.7	15.6	0.0		
E4-2	Mineral Wool	4.1	190	60				0.00		-22.1	-8.0	0.0		
E4-3	Mineral Wool	4.1	190	90				0.00		-1.8	-0.9	0.0		
C4-1	Mineral Wool	8	190	30		0.641	0.0018	3.37		0.0	10.2	0.6		
C4-2	Mineral Wool	8	190	60				0.50		0.0	4.3	-0.2		
C4-3	Mineral Wool	8	190	90				0.97		0.0	7.1	0.1		
R6-1	Mineral Wool	8	190	30		0.9292	0.0097	19.36		45.2	36.7	10.0		
R6-2	Mineral Wool	8	190	60				3.58		4.8	12.3	0.4		
R6-3	Mineral Wool	8	190	90				-1.82		-3.8	-3.0	-1.8		
D4-1	Mineral Wool	12	190	30		0.64	0.0065	12.82		18.1	70.7	1.5		
D4-2	Mineral Wool	12	190	60				16.26		37.3	111.6	1.1		
D4-3	Mineral Wool	12	190	90				10.20		42.3	67.5	0.6		
K3-1	Mineral Wool	4.1	265	30		0.9288	0.052	6.45		21.1	22.0	0.0		
K3-2	Mineral Wool	4.1	265	60				-0.87		8.8	3.8	0.0		
K3-3	Mineral Wool	4.1	265	90				3.37		20.9	15.0	0.0		
H4-1	Mineral Wool	8	265	30		0.9301	0.0548	13.68		17.4	48.5	0.0		
H4-2	Mineral Wool	8	265	60				10.04		14.7	35.2	0.0		
H4-3	Mineral Wool	8	265	90				0.71		3.0	3.0	0.0		
L3-1	Mineral Wool	8	265	30		0.9298	0.0312	22.46		63.9	80.1	0.0		
L3-2	Mineral Wool	8	265	60				2.26		11.3	9.8	0.0		
L3-3	Mineral Wool	8	265	90				-2.62		-6.9	-10.3	0.0		
M3-1	Mineral Wool	12	265	30		0.9288	0.0923	25.41		9.6	305.0	3.8		
M3-2	Mineral Wool	12	265	60				34.72		63.9	51.7	0.5		
M3-3	Mineral Wool	12	265	90				-5.88		-3.0	-20.0	-1.1		
E7-1	Min-K	4.1	190	30		0.0255	0.0075	0.00		253.2	432.9	0.0		
E7-2	Min-K	4.1	190	60				0.00		-6.8	-241.5	0.0		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _i	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² -min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² -min	Zn Rel Rate / Area mg/m ² -min
E7-3	Min-K	4.1	190	90				0.00		-25.2	117.4	0.0		
Q2-1	MIN-K	4.1	190	30		0.0372	0.0188	112.51		215.9	1581.7	30.9		
Q2-2	MIN-K	4.1	190	60				-5.68		-71.8	-229.3	9.5		
Q2-3	MIN-K	4.1	190	90				19.39		43.7	-131.5	2.2		
C7-1	Min-K	8	190	30		0.0259	0.0064	79.05		24.3	5682.5	40.6		
C7-2	Min-K	8	190	60				-0.66		-18.6	3858.2	-6.5		
C7-3	Min-K	8	190	90				-0.91		0.0	1446.7	-1.7		
R2-1	MIN-K	8	190	30		0.0374	0.0091	202.92		478.0	10343.0	64.6		
R2-2	MIN-K	8	190	60				-3.29		-81.8	5411.1	-11.3		
R2-3	MIN-K	8	190	90				60.01		196.2	4681.4	42.8		
D7-1	Min-K	12	190	30		0.0258	0.0078	130.48		0.0	13560.0	88.6		
D7-2	Min-K	12	190	60				-1.64		0.0	2633.0	12.2		
D7-3	Min-K	12	190	90				7.24		0.0	2022.5	16.6		
K8-1	Min-K	4.1	265	30		0.0373	0.0135	936.31		446.0	4272.9	9.0		
K8-2	Min-K	4.1	265	60				-510.38		-181.9	203.5	-8.0		
K8-3	Min-K	4.1	265	90				-192.67		-15.6	1625.6	0.0		
L8-1	Min-K	8	265	30		0.0374	0.0169	132.33		290.8	4581.2	0.0		
L8-2	Min-K	8	265	60				178.57		34.7	2722.3	0.0		
L8-3	Min-K	8	265	90				-84.96		-36.0	-2225.0	0.0		
M8-1	MIN-K	12	265	30		0.0373	0.0241	198.93		87.3	14823.8	52.4		
M8-2	Min-K	12	265	60				577.16		24.1	-1360.5	2.0		
M8-3	Min-K	12	265	90				686.15		57.6	-1688.7	6.2		
B1-1	Nukon	4.1	190	30		0.898	0.0091	2.56		0.0	3.6	8.1		
B1-2	Nukon	4.1	190	60				0.00		0.0	2.0	-3.8		
B1-3	Nukon	4.1	190	90				0.06		0.0	3.5	2.3		
E1-1	Nukon	4.1	190	30		0.9	0.0177	1.10		14.6	13.5	7.1		
E1-2	Nukon	4.1	190	60				-0.40		-2.2	-1.1	0.1		
E1-3	Nukon	4.1	190	90				-0.49		-0.3	-0.3	-1.1		
C1-1	Nukon	8	190	30		0.905	0.0139	2.27		0.0	19.7	6.1		
C1-2	Nukon	8	190	60				-0.29		0.0	-12.1	-4.8		
C1-3	Nukon	8	190	90				0.78		0.0	34.6	3.3		
R5-1	Nukon	8	190	30		1.3002	0.036	11.79		27.8	67.4	20.0		
R5-2	Nukon	8	190	60				18.85		1.1	22.0	-1.4		
R5-3	Nukon	8	190	90				-14.05		1.4	29.1	-0.6		
D1-1	Nukon	12	190	30		0.909	0.0452	3.71		0.0	47.9	1.8		
D1-2	Nukon	12	190	60				-0.14		0.0	-9.7	-1.6		
D1-3	Nukon	12	190	90				-0.31		0.0	-13.4	0.0		
K6-1	Nukon	4.1	265	30		1.2997	0.0744	8.44		22.2	70.0	0.0		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH _i	T °F	Time min	Surf. Area cm ²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m ² - min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m ² - min	Zn Rel Rate / Area mg/m ² - min
K6-2	Nukon	4.1	265	60				-4.30		3.4	7.7	0.0		
K6-3	Nukon	4.1	265	90				0.18		4.8	32.0	0.0		
L6-1	Nukon	8	265	30		1.3007	0.0784	9.14		28.0	167.8	4.2		
L6-2	Nukon	8	265	60				2.91		26.9	51.2	-0.6		
L6-3	Nukon	8	265	90				0.21		-16.7	2.5	-0.9		
M6-1	Nukon	12	265	30		1.3012	0.1428	37.33		59.2	764.1	16.2		
M6-2	Nukon	12	265	60				-9.96		-18.2	-203.6	-6.8		
M6-3	Nukon	12	265	90				3.06		-5.6	136.5	-2.3		
P1-1	Steel	4.1	190	30	35	5.5708	-0.004						2.8	
P1-2	Steel	4.1	190	60	35								8.6	
P1-3	Steel	4.1	190	90	35								10.8	
Q5-1	Steel	8	190	30	35	11.1945	0.0019						0.0	
Q5-2	Steel	8	190	60	35								0.0	
Q5-3	Steel	8	190	90	35								0.0	
P5-1	Steel	12	190	30	35	5.1959	-0.0013						0.2	
P5-2	Steel	12	190	60	35								-0.1	
P5-3	Steel	12	190	90	35								0.1	
O1-1	Steel	4.1	265	30	35	5.0217	0.003						0.4	
O1-2	Steel	4.1	265	60	35								3.7	
O1-3	Steel	4.1	265	90	35								1.4	
N5-1	Steel	8	265	30	35	6.3007	0.0012						0.0	
N5-2	Steel	8	265	60	35								0.0	
N5-3	Steel	8	265	90	35								1.3	
N1-1	Steel	12	265	30	35	5.7289	-0.001						0.8	
N1-2	Steel	12	265	60	35								0.1	
N1-3	Steel	12	265	90	35								0.0	

APPENDIX B: HIGH MAGNIFICATION SEM OF PRECIPITATES

SEM analyses were performed on the thirteen precipitates formed during bench testing in order to estimate the size of each precipitate's constituent particles. The high magnification pictures are attached below.

Figure B-1: High Magnification SEM of PPT1

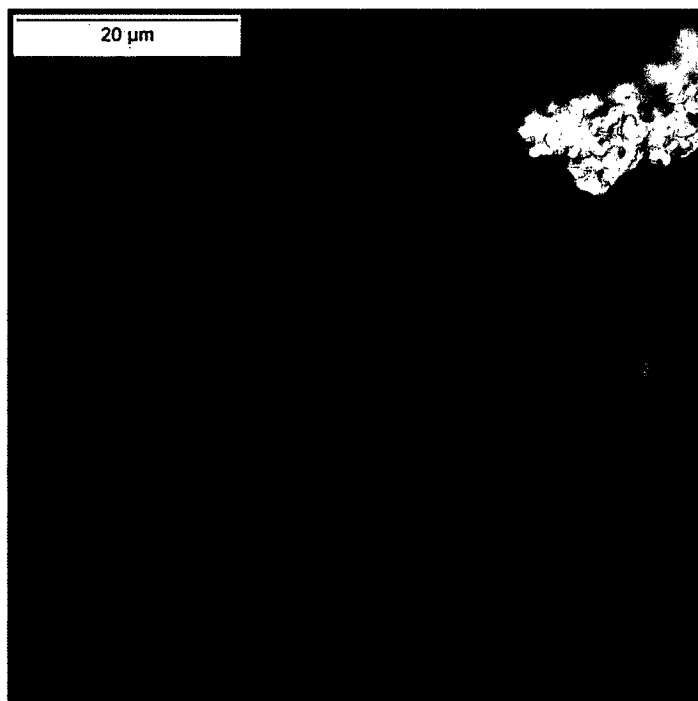


Figure B-2: High Magnification SEM of PPT2

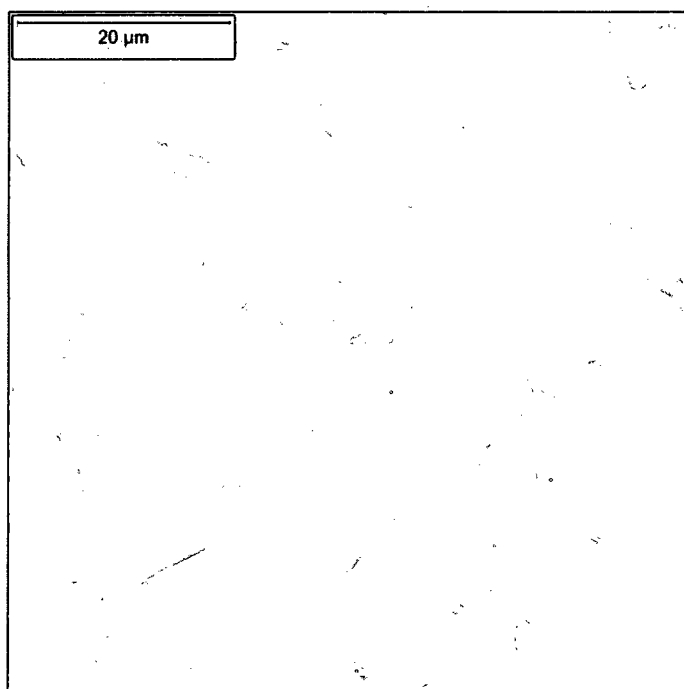


Figure B-3: High Magnification SEM of PPT3

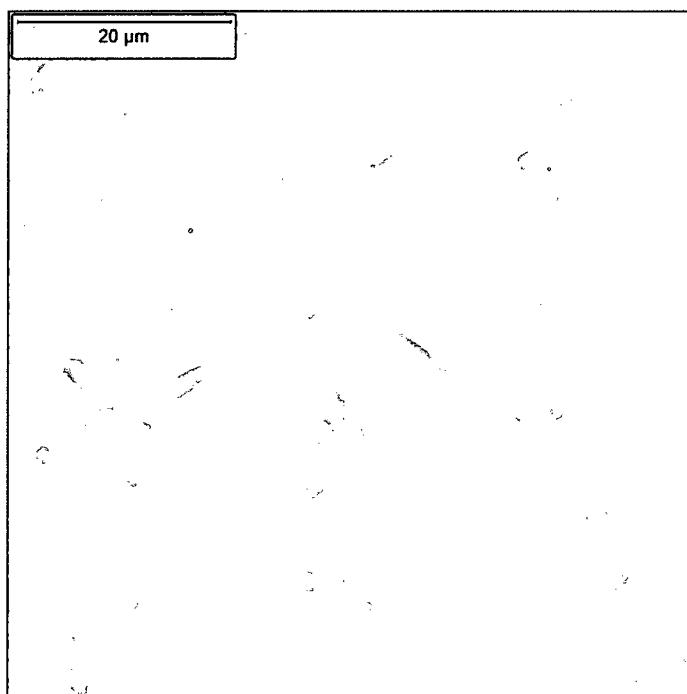


Figure B-4: High Magnification SEM of PPT12

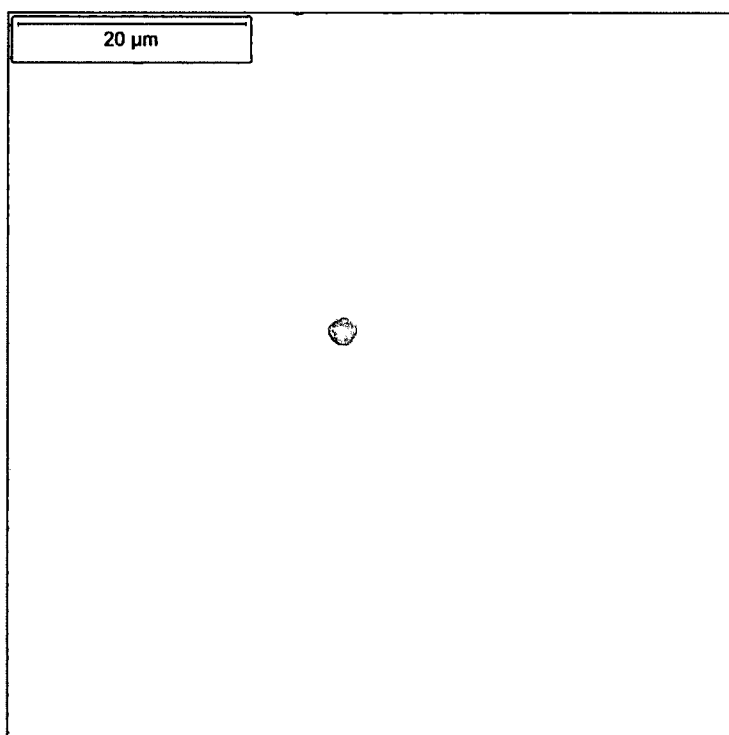


Figure B-5: High Magnification SEM of PPT13

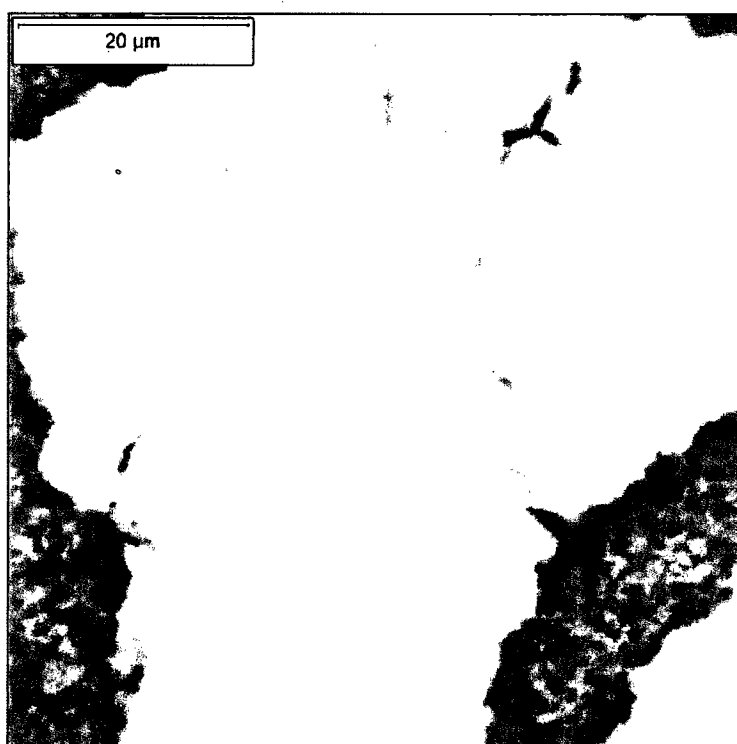


Figure B-6: High Magnification SEM of PPT14

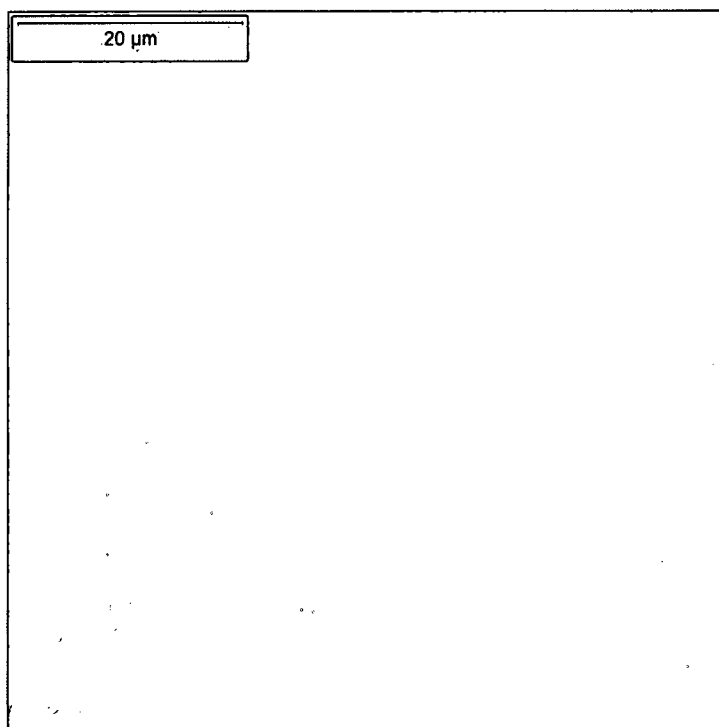


Figure B-7: High Magnification SEM of PPT16

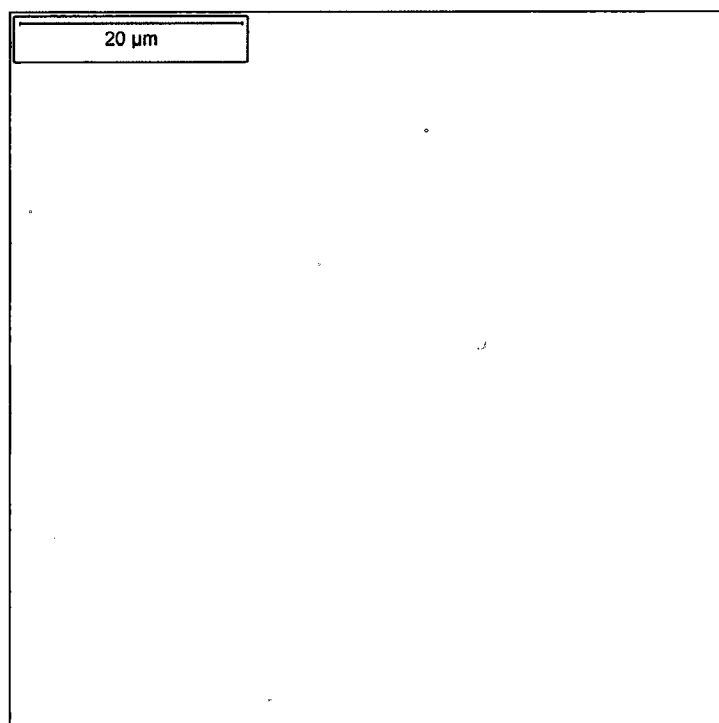


Figure B-8: High Magnification SEM of PPT22

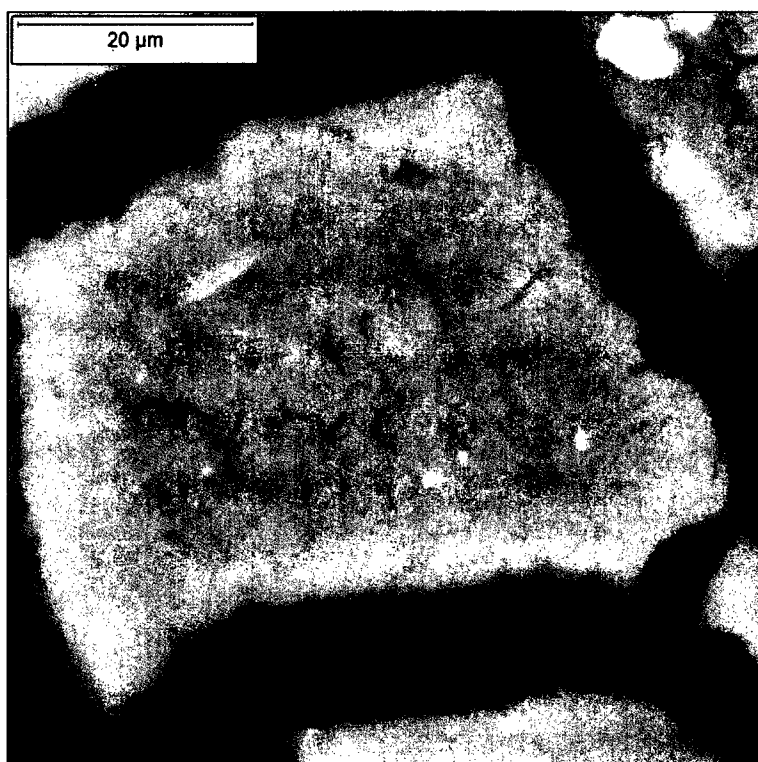


Figure B-9: High Magnification SEM of PPT24

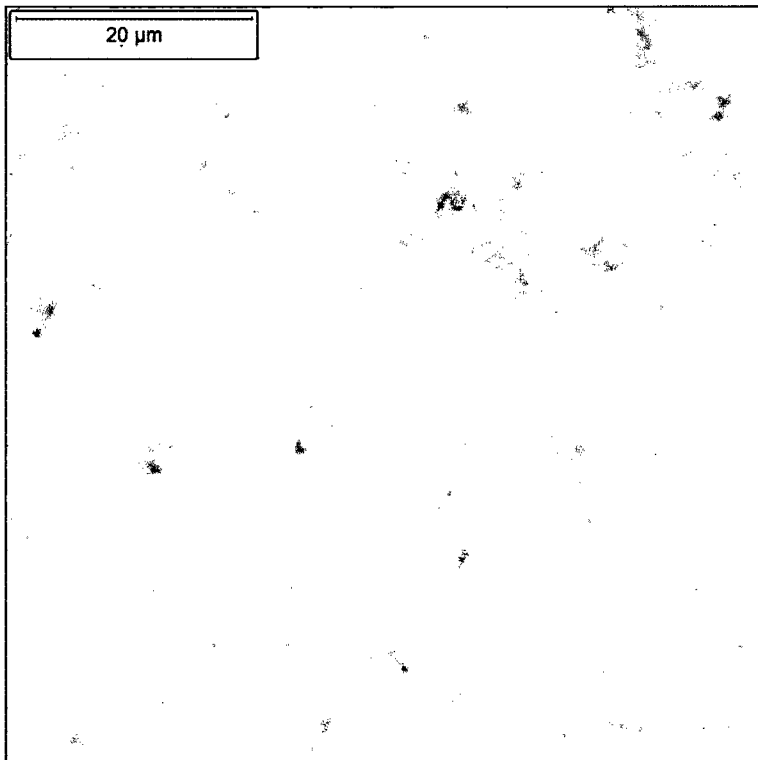


Figure B-10: High Magnification SEM of PPT30

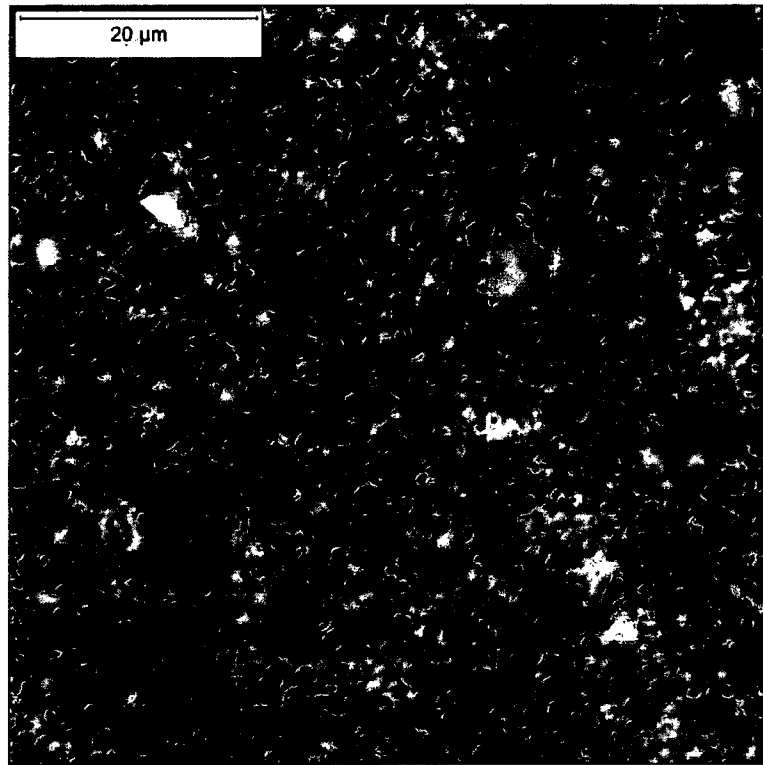


Figure B-11: High Magnification SEM of PPT35

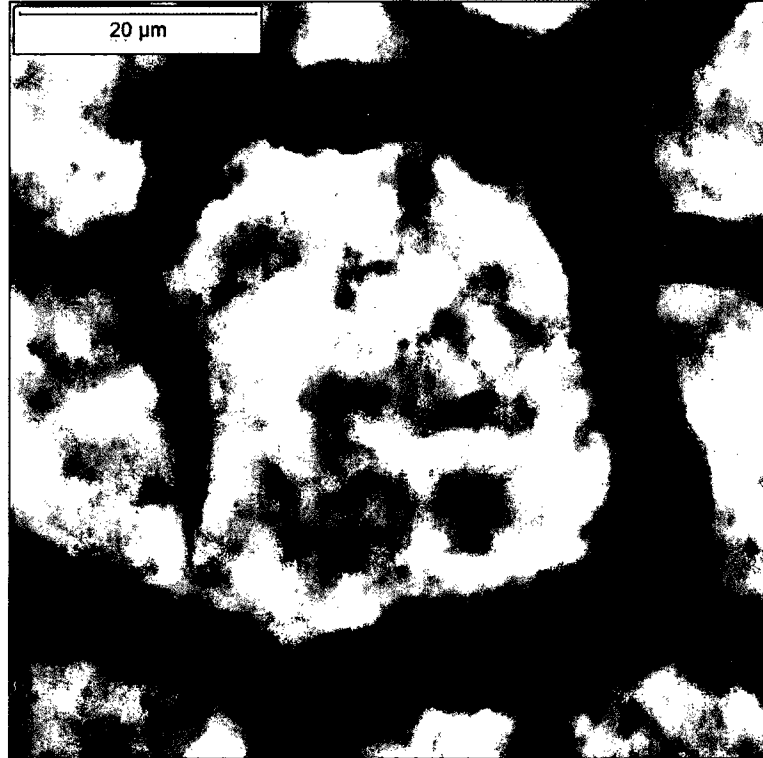


Figure B-12: High Magnification SEM of PPT38

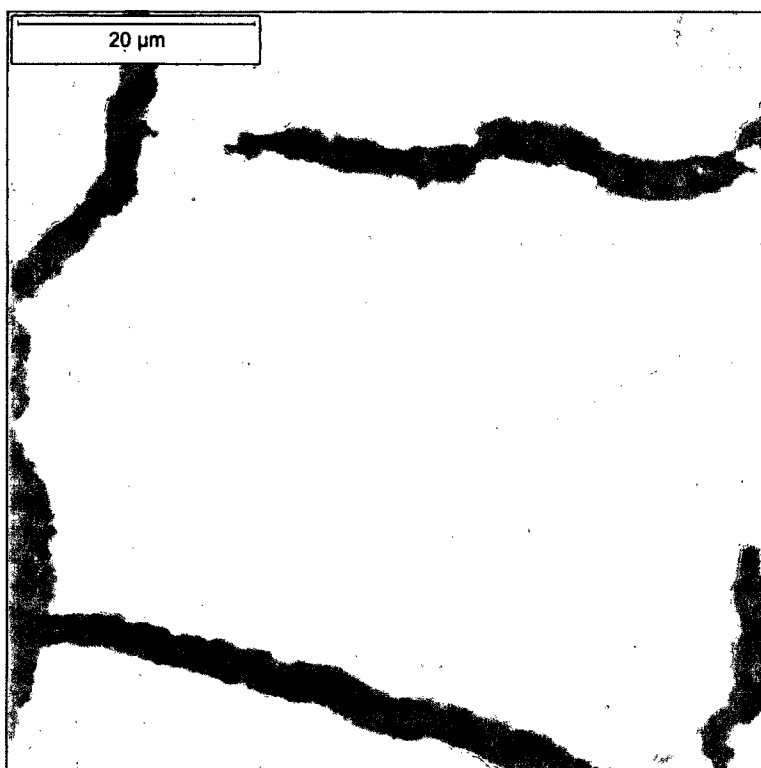
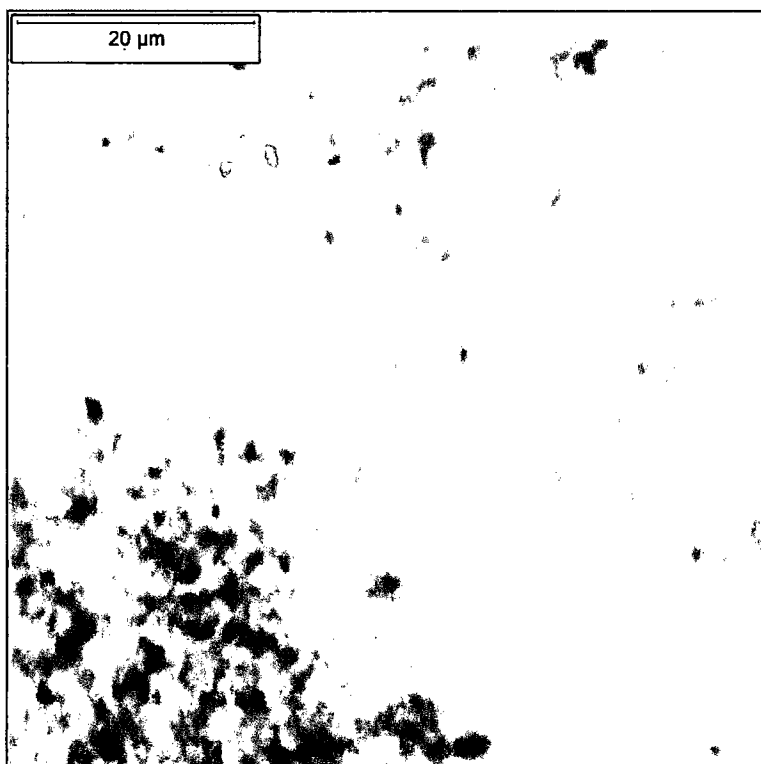


Figure B-13: High Magnification SEM of PPT60



APPENDIX C: FILTERABILITY TEST DATA

The figures attached below contain the pressure drop versus flow rate data from the filterability tests performed on the precipitates produced during bench testing. A figure has been generated for each precipitate formed either by cooling or by chemical reaction due to pH adjustment or material combinations. Table C-1 summarizes the filter coefficient results calculated from this data in Section 5.3.

Table C-1: Summary of Filter K_f Results

PPT Run	Mass of PPT Filtered (g)	Method of Precipitation Formation	Slope of filtration curve (psi-min/ml)	Area (ft ²)	Temp. (F)	K_f	K_{fx}	Viscosity (cP)	Temp. Corrected K_{fs}
1	0.0001	PPT on cooling, Al, pH 4	-0.0005	0.004	77.9	-108.75	-0.0004	0.881	5.72
2	0.0408	PPT on cooling, Al, pH 8	0.3891	0.004	76.7	0.15	0.0033	0.894	5.80
3	0.0362	PPT on cooling, Al, pH 12	-0.0992	0.004	75	-0.59	-0.0105	0.914	5.93
3a	0.0013	PPT on cooling, Al, pH 12	0.0632	0.004	75	0.93	0.0008	0.914	5.93
12	0.0012	PPT on cooling, Other Fiberglass, pH 12	0.0568	0.004	76	1.15	0.0009	1.015	6.59
13	0.0005	PPT on cooling, Concrete, pH 4	0.0293	0.004	77	1.96	0.0008	0.891	5.78
14	0.0048	PPT on cooling, Concrete, pH 8	0.0106	0.004	77	5.45	0.2424	0.891	5.78
16	-0.0001	PPT on cooling, Mineral Wool, pH 4	0.0132	0.004	77	4.35	-0.0009	0.891	5.78
22	0.0003	PPT on cooling, FiberFax, pH 4	0.0263	0.004	78	2.16	0.0006	0.880	5.71
24a	0.0048	PPT on cooling, Fiberfrax, pH 12	0.0342	0.004	71.1	1.81	0.0066	0.961	6.24
24b	0.0048	PPT on cooling, Fiberfrax, pH 12	0.0450	0.004	75.7	1.30	0.0043	0.905	5.88
24c	0.0048	PPT on cooling, Fiberfrax, pH 12	0.0674	0.004	74.8	0.88	0.0027	0.916	5.95
24d	0.0048	PPT on cooling, Fiberfrax, pH 12	0.0484	0.004	77.1	1.19	0.0039	0.890	5.78
30	0.0005	PPT on cooling, Galvanized, pH 12	0.0114	0.004	77.7	4.98	0.0103	0.883	5.73
35	0.0021	PPT of Phosphates, CalSil	0.0294	0.004	78	1.93	0.0033	0.880	5.71
38	0.0041	PPT of Phosphates, Powdered Concrete	1.082	0.004	78	0.05	0.0001	0.880	5.71
60	0.0011	pH 12 265 Fiberglass (high sulfur), with high calcium from pH 4 CalSil. CaSO ₄ PPT?	0.0303	0.004	78	1.87	0.0017	0.880	5.71
blank filter	--	--	0.00995	0.004	72.6	6.12	--	0.942	6.12

Figure C-1 – dP vs. Flow for a Blank Filter @ 72.6°F (15 to 60 ml/min only)

($n = .9358$ cP; $z_s = 0.009948537 \pm 0.000206245$ psi-min/ml)

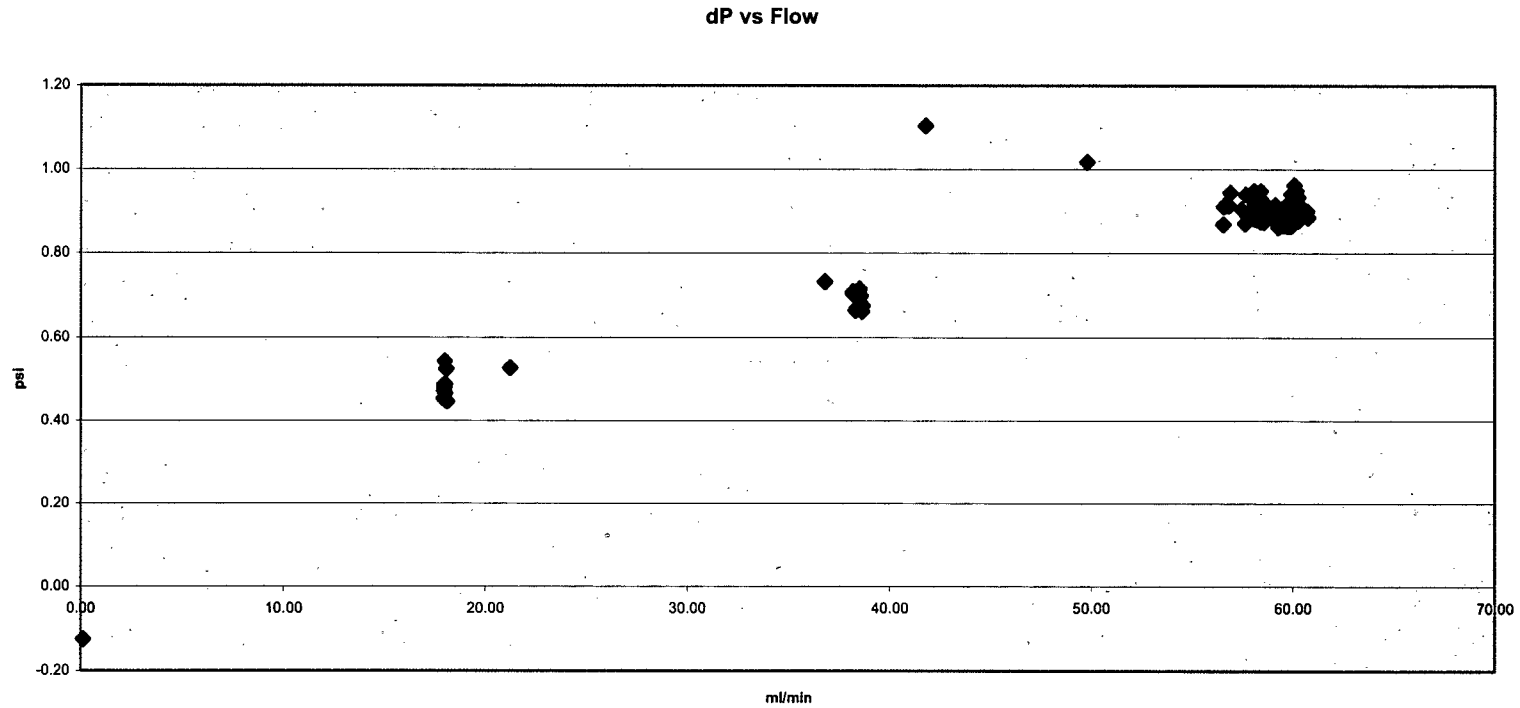


Figure C-2 – dP vs. Flow for PPT 24a @ 71.1°F

(n = .9579 cP; z = 0.034195272 +/- 0.00125012 psi-min/ml)

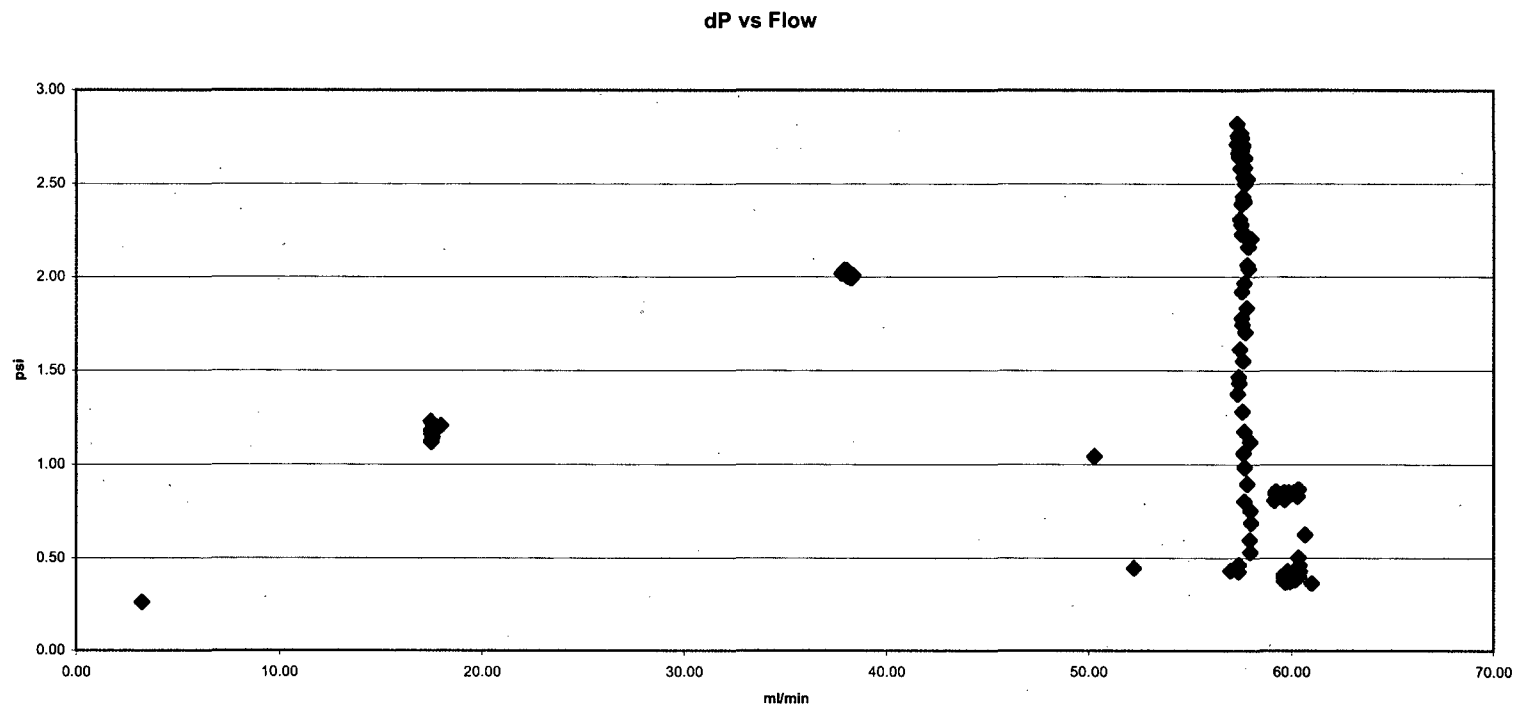


Figure C-3 – dP vs. Flow for PPT 24b @ 75.7°F

($n = .9142$ cP; $z = 0.045015726 \pm 0.000439639$ psi-min/ml)

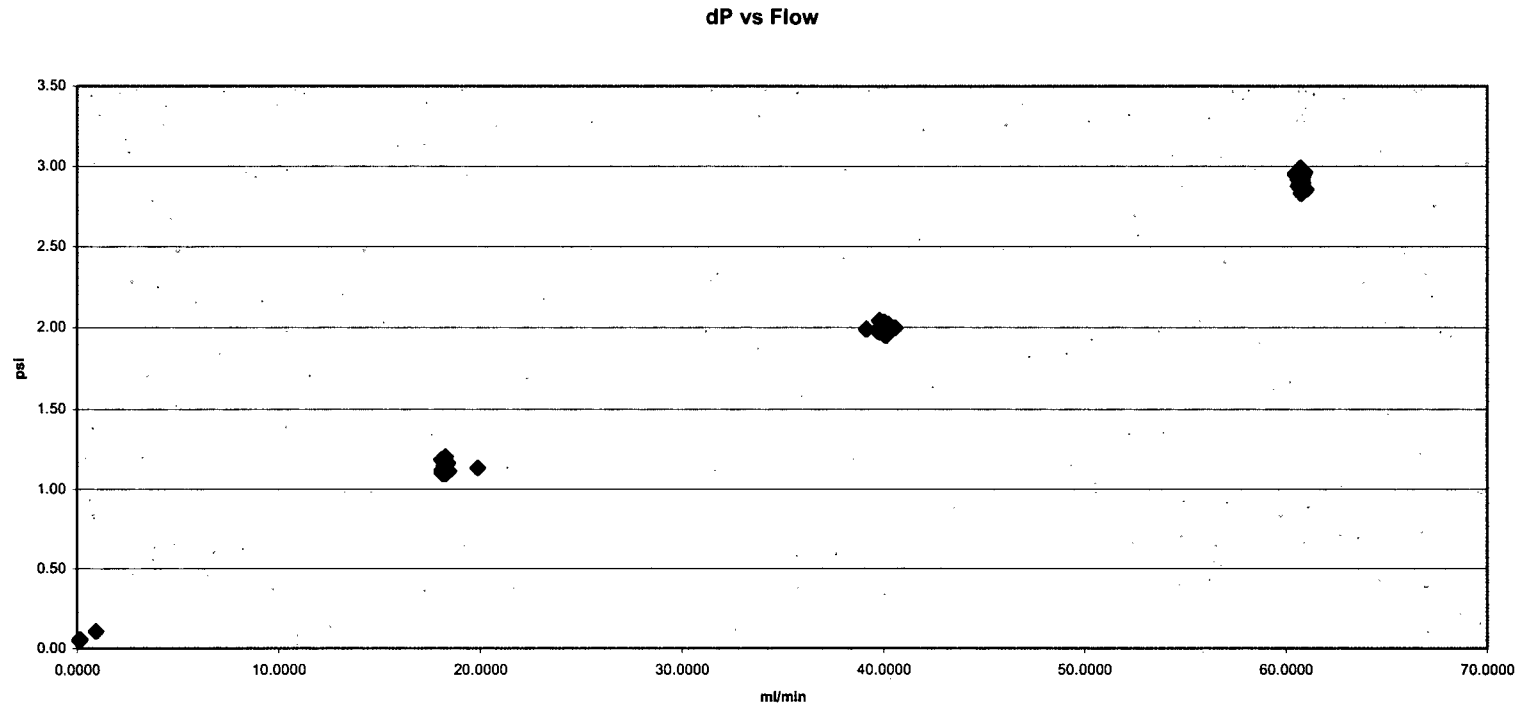


Figure C-4 – dP vs. Flow for PPT 24c @ 74.8°F

(n = .9142 cP; z = 0.067356571 +/- 0.000738347 psi-min/ml)

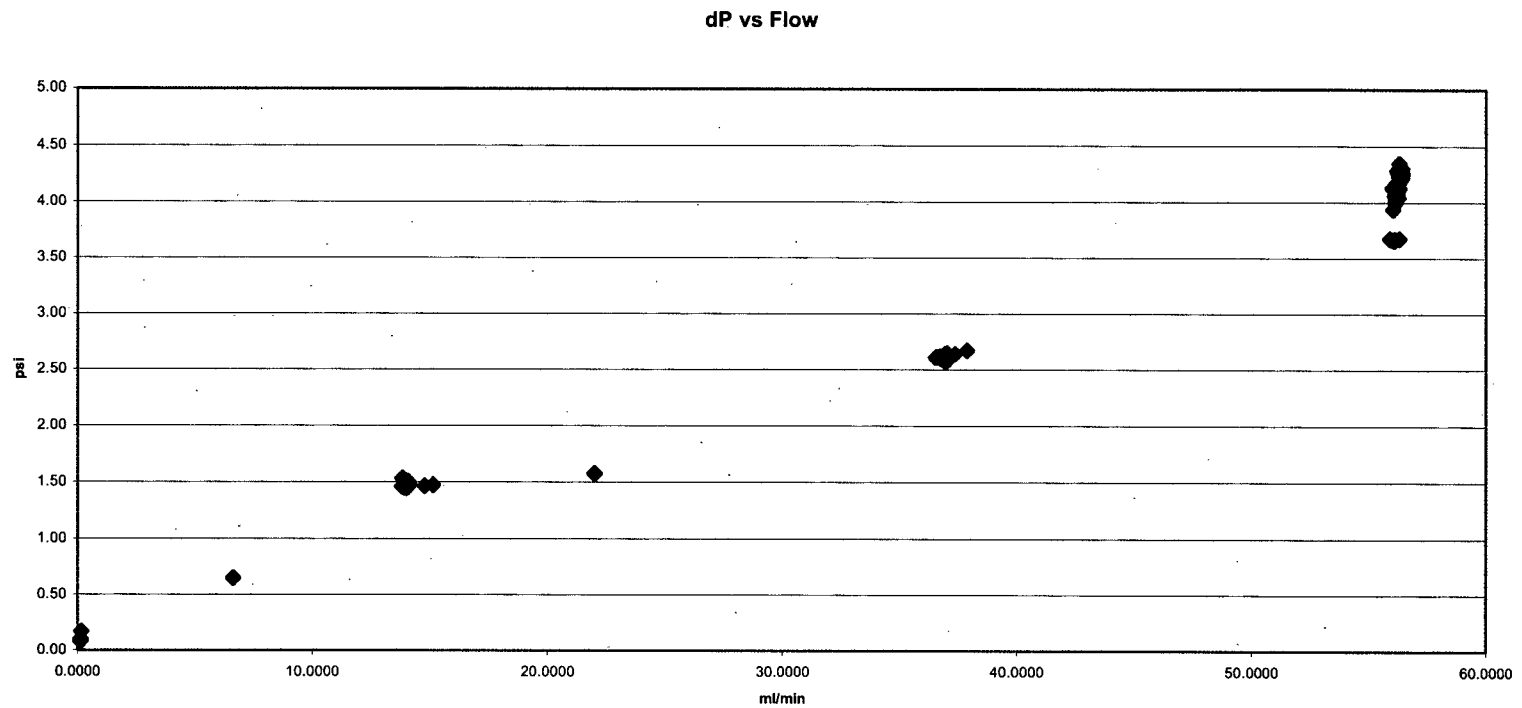


Figure C-5 – dP vs. Flow for PPT 24d @ 77.1°F

(n = .8937 cP; z = 0.048421822+/- 0.00103711 psi-min/ml)

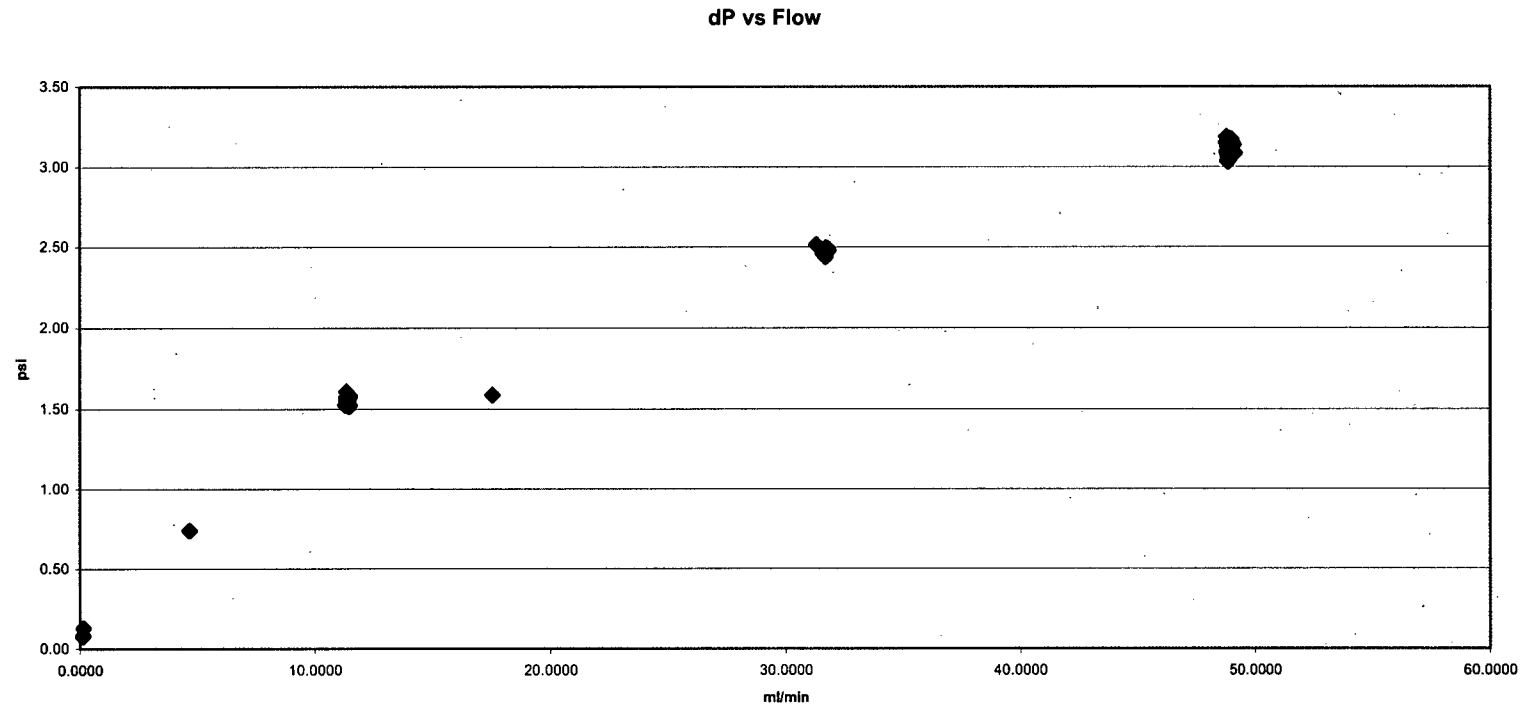


Figure C-6 – dP vs. Flow for PPT 1 @ 77.8°F

(n = .8737 cP; z = -0.000523053+/- 0.000184422 psi-min/ml)

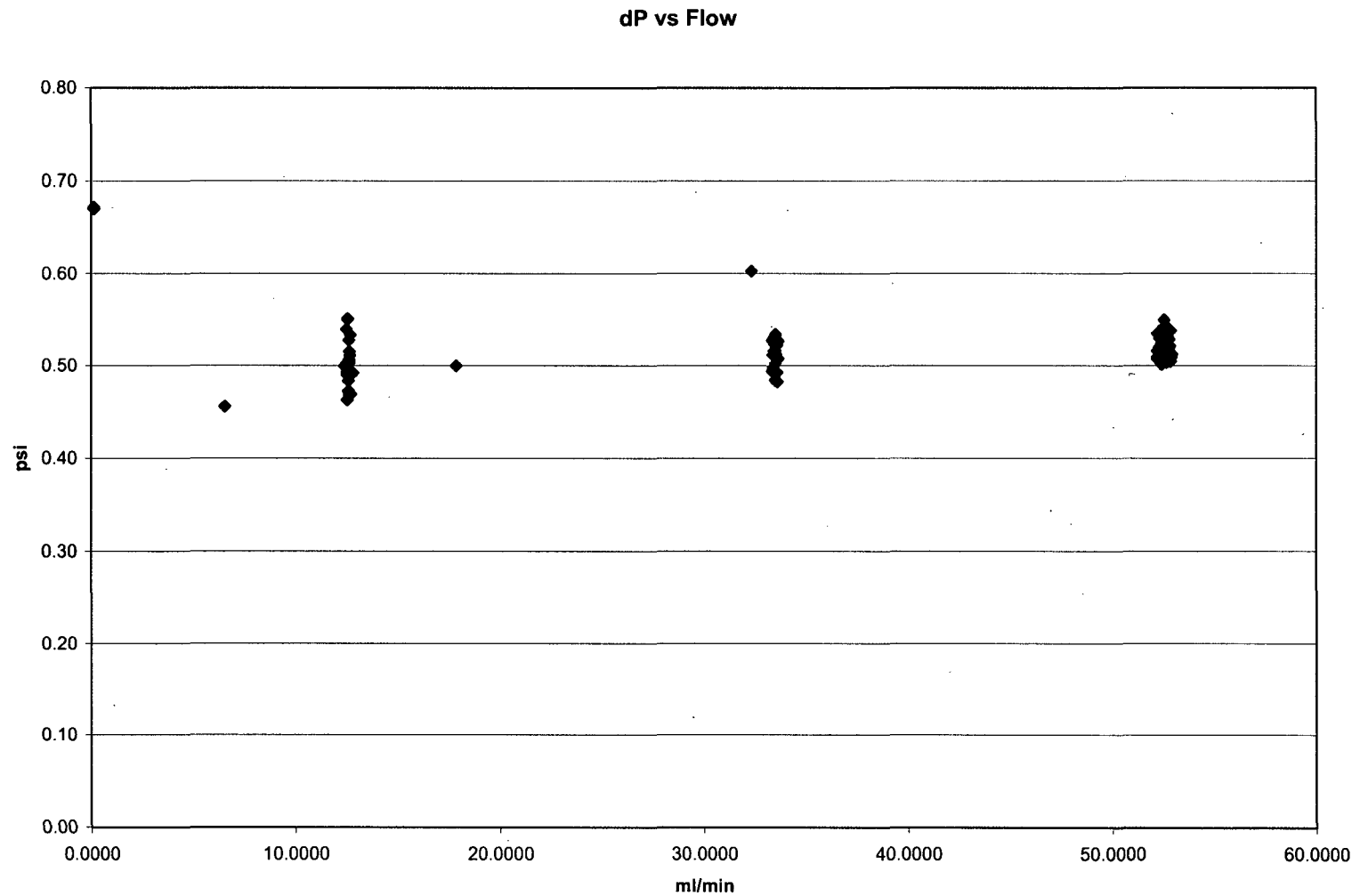


Figure C-7 – dP vs. Flow for PPT2 @ 77.8°F

(n = .8937 cP; z = 0.389122659+/- 0.00238118 psi-min/ml)

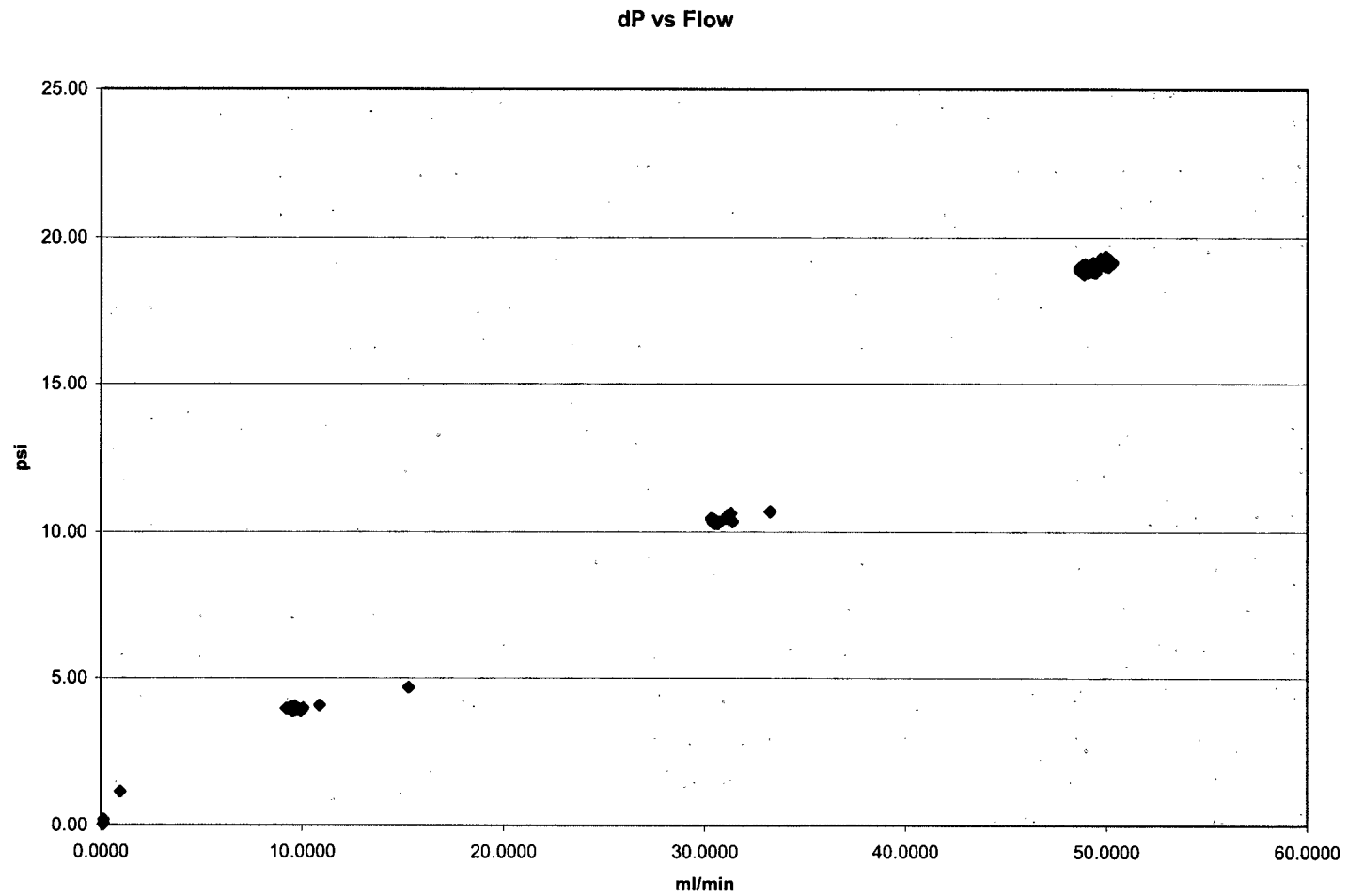


Figure C-8 – dP vs. Flow for PPT3 @ 67°F (7 to 48 ml/min only)

(n = 1.005 cP; z = 0.06320968+/-0.006169918 psi-min/ml)

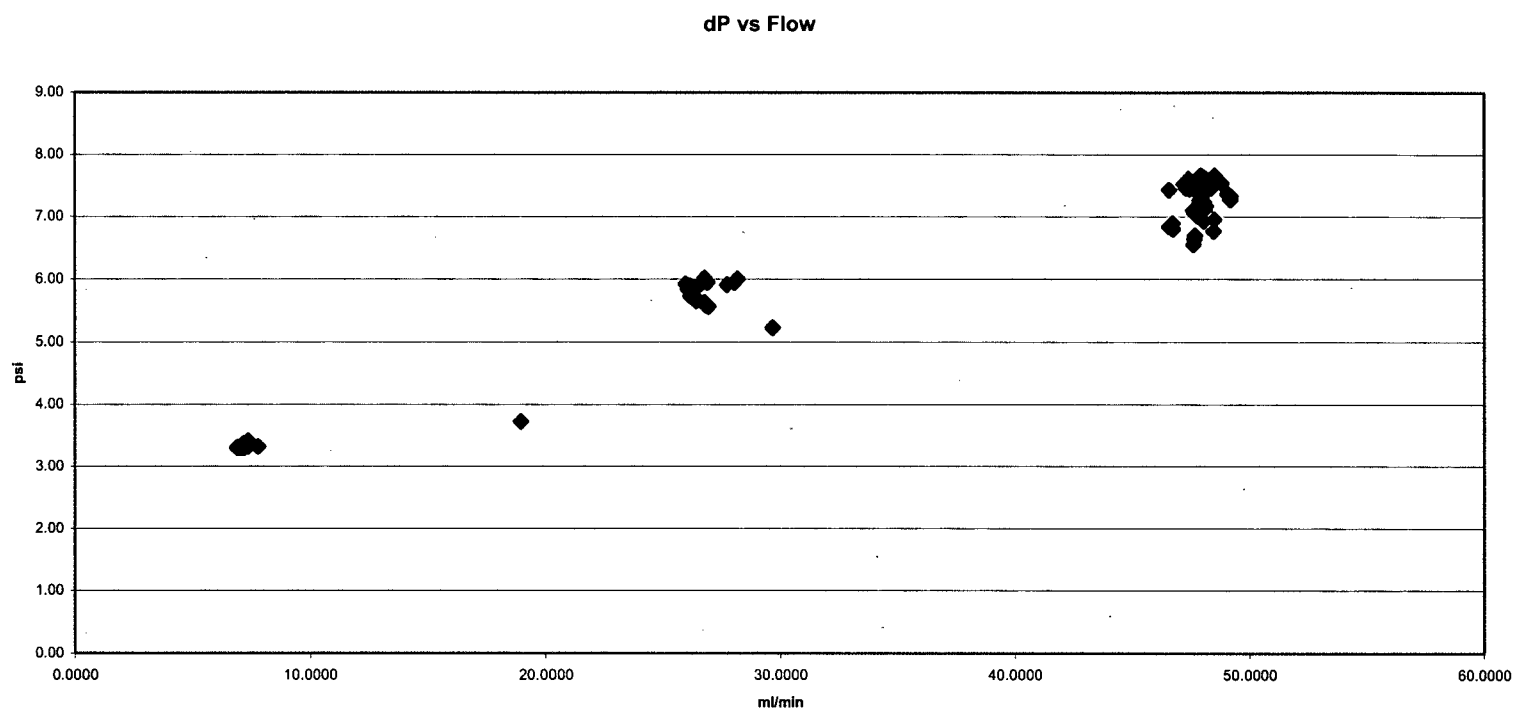


Figure C-9 – dP vs. Flow for PPT12 @ 76°F

(n = .8937 cP; z = 0.056765318+/- 0.000979488psi-min/ml)

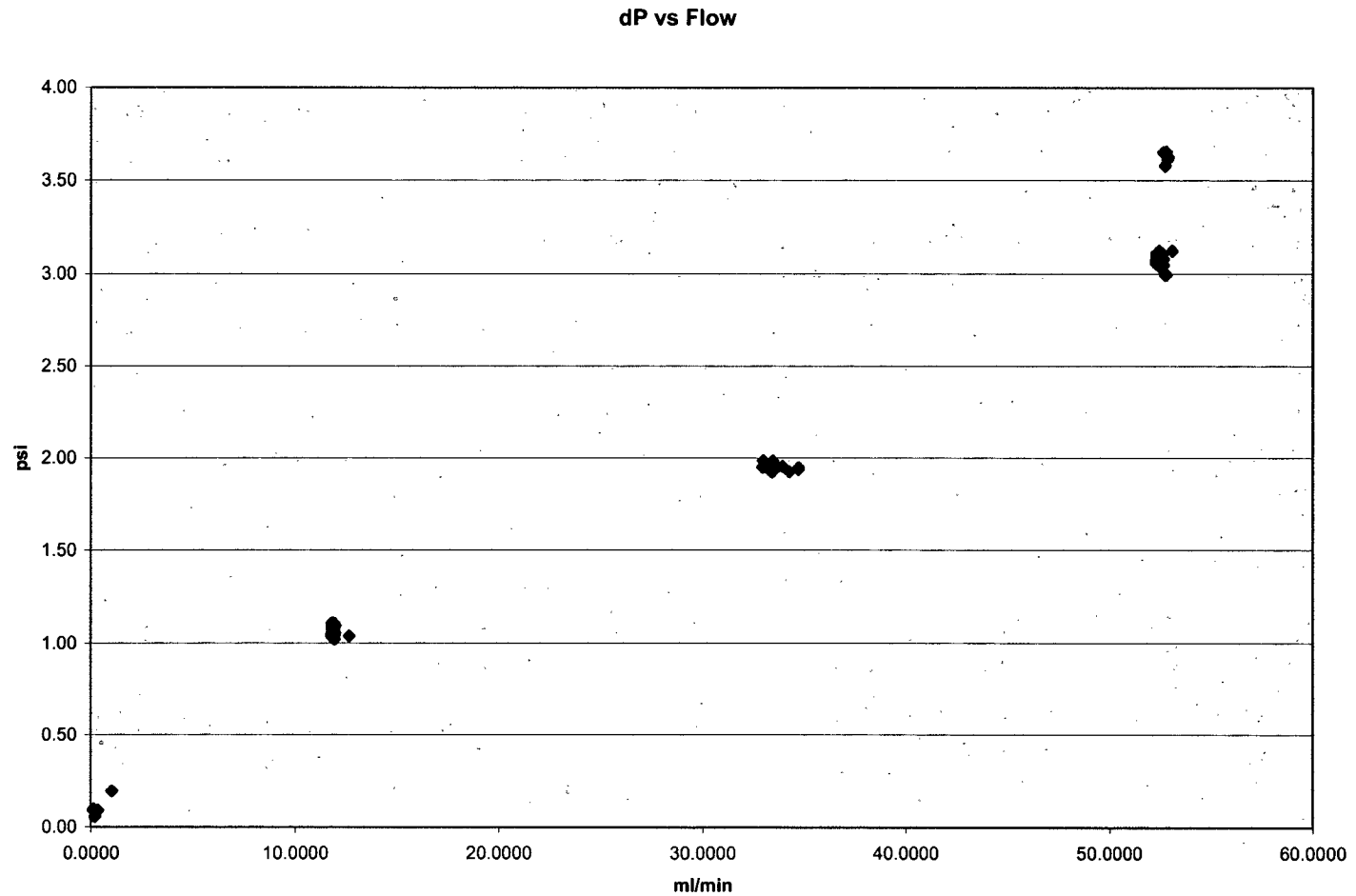


Figure C-10 – dP vs. Flow for PPT13 @ 77°F (0 to 13 ml/min only)

($n = .8937$ cP; $z = 0.029311817 \pm 0.001103119$ psi-min/ml)

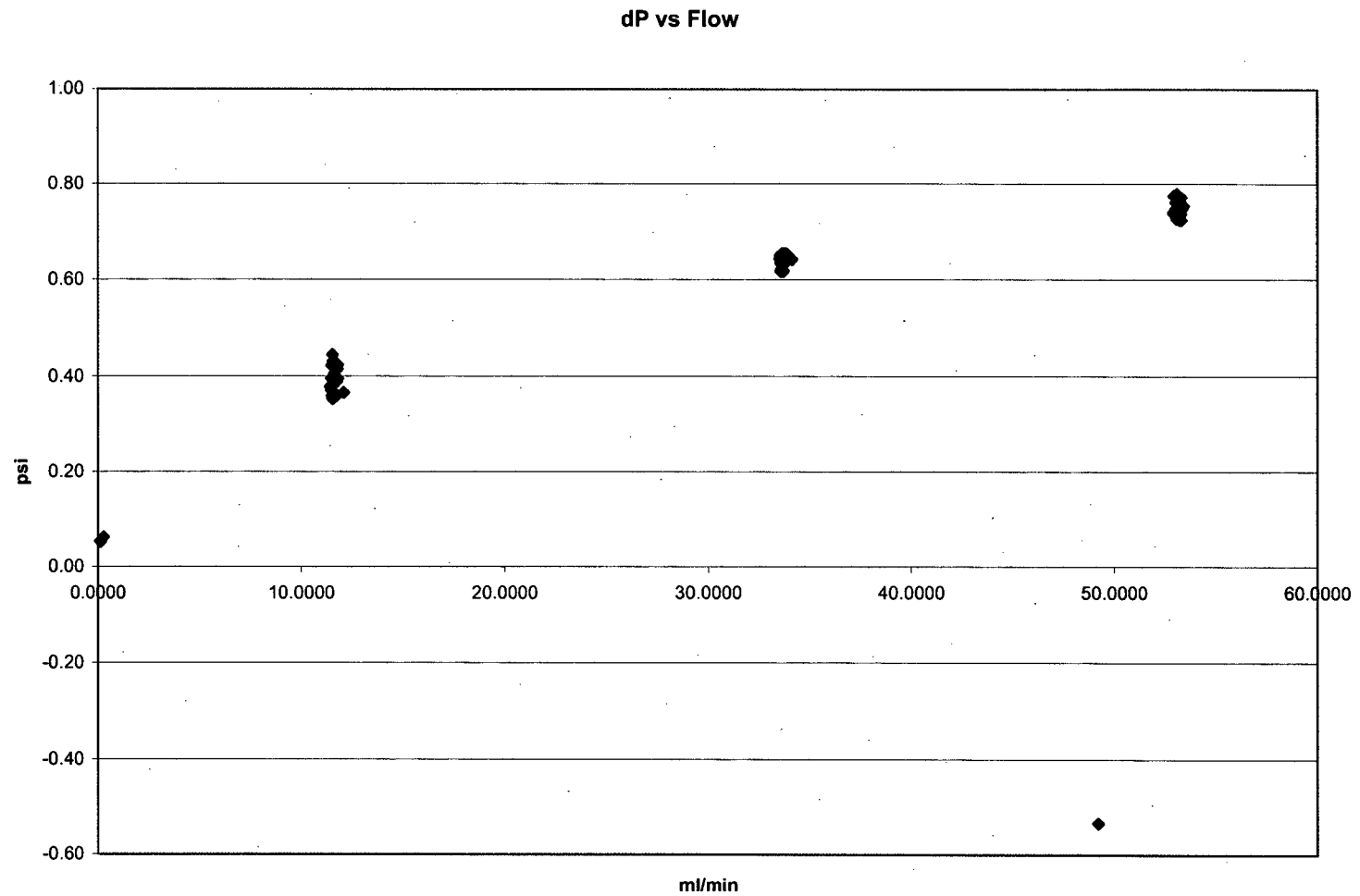


Figure C-11 – dP vs. Flow for PPT14 @ 77°F (0 to 33 ml/min only)

($n = .8937$ cP; $z = 0.010562088 \pm 0.000318675$ psi-min/ml)

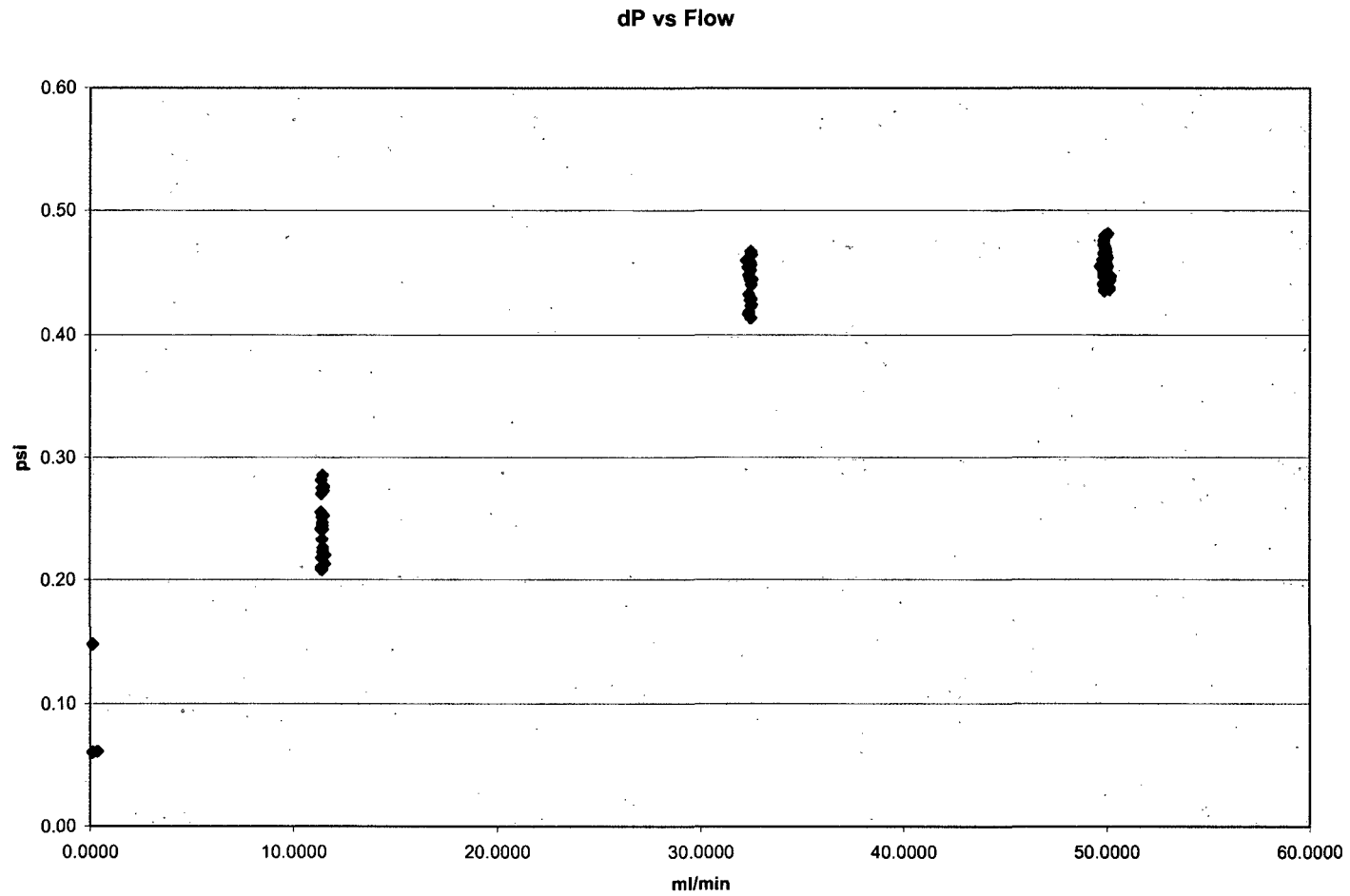


Figure C-12 – dP vs. Flow for PPT16 @ 78°F (0 to 30 ml/min only)

($n = .8737$ cP; $z = 0.013211422 \pm 0.000471689$ psi-min/ml)

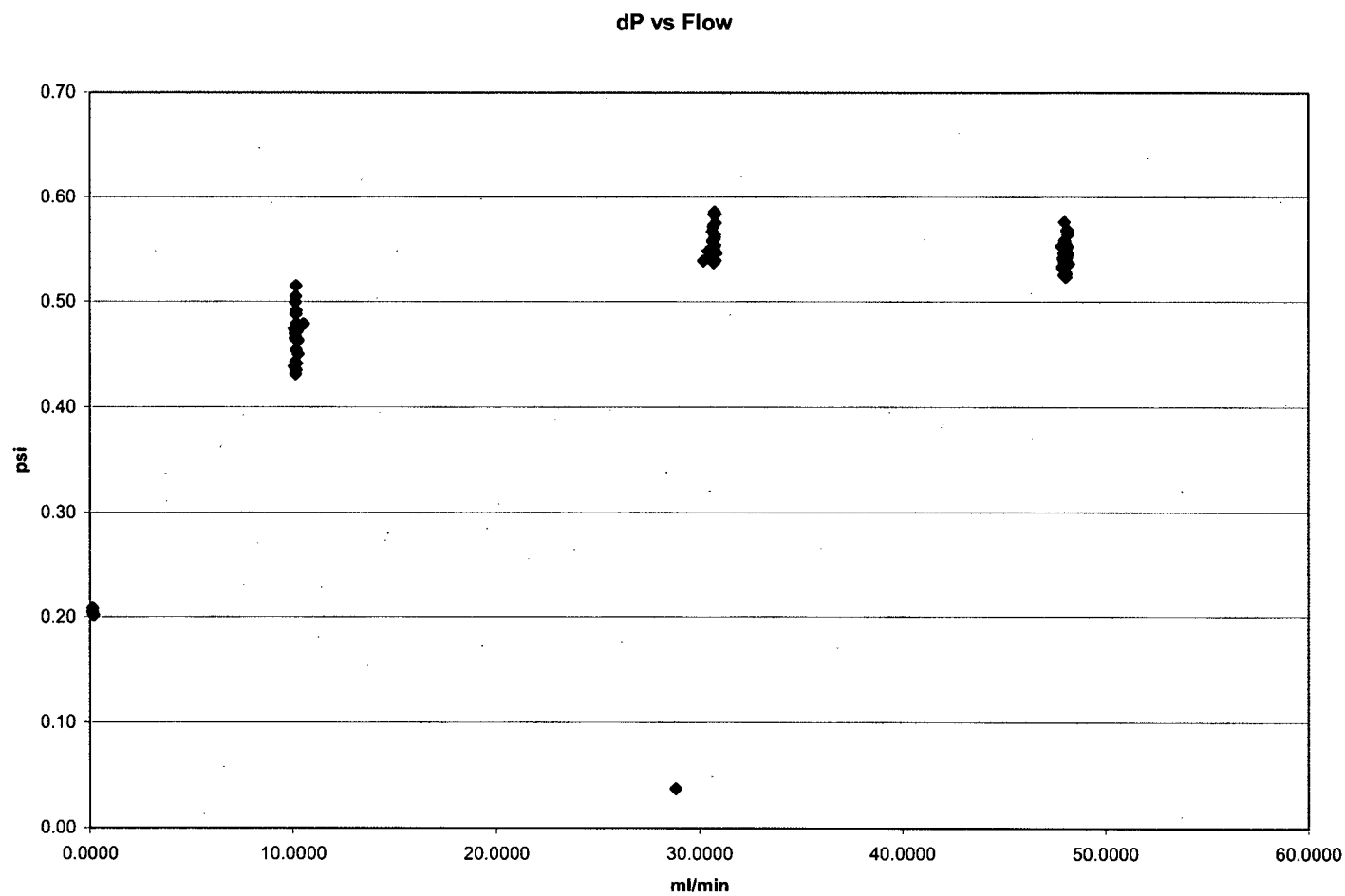


Figure C-13 – dP vs. Flow for PPT22 @ 78°F (0 to 10 ml/min only)

($n = .8737$ cP; $z = 0.026327465 \pm 0.000526035$ psi-min/ml)

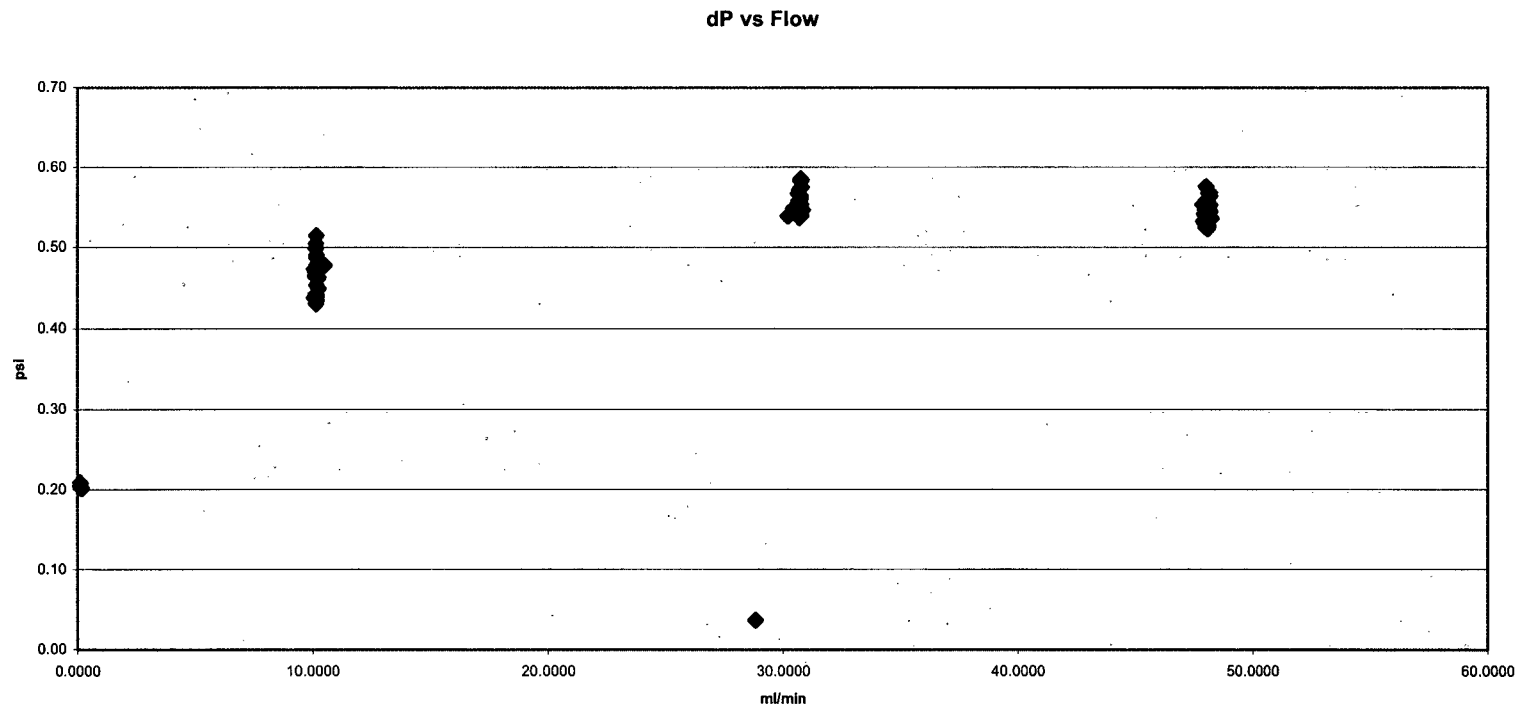


Figure C-14 – dP vs. Flow for PPT30 @ 77.7°F (0 to 35 ml/min only)

($n = .8737$ cP; $z = 0.011444646 \pm 0.001024822$ psi-min/ml)

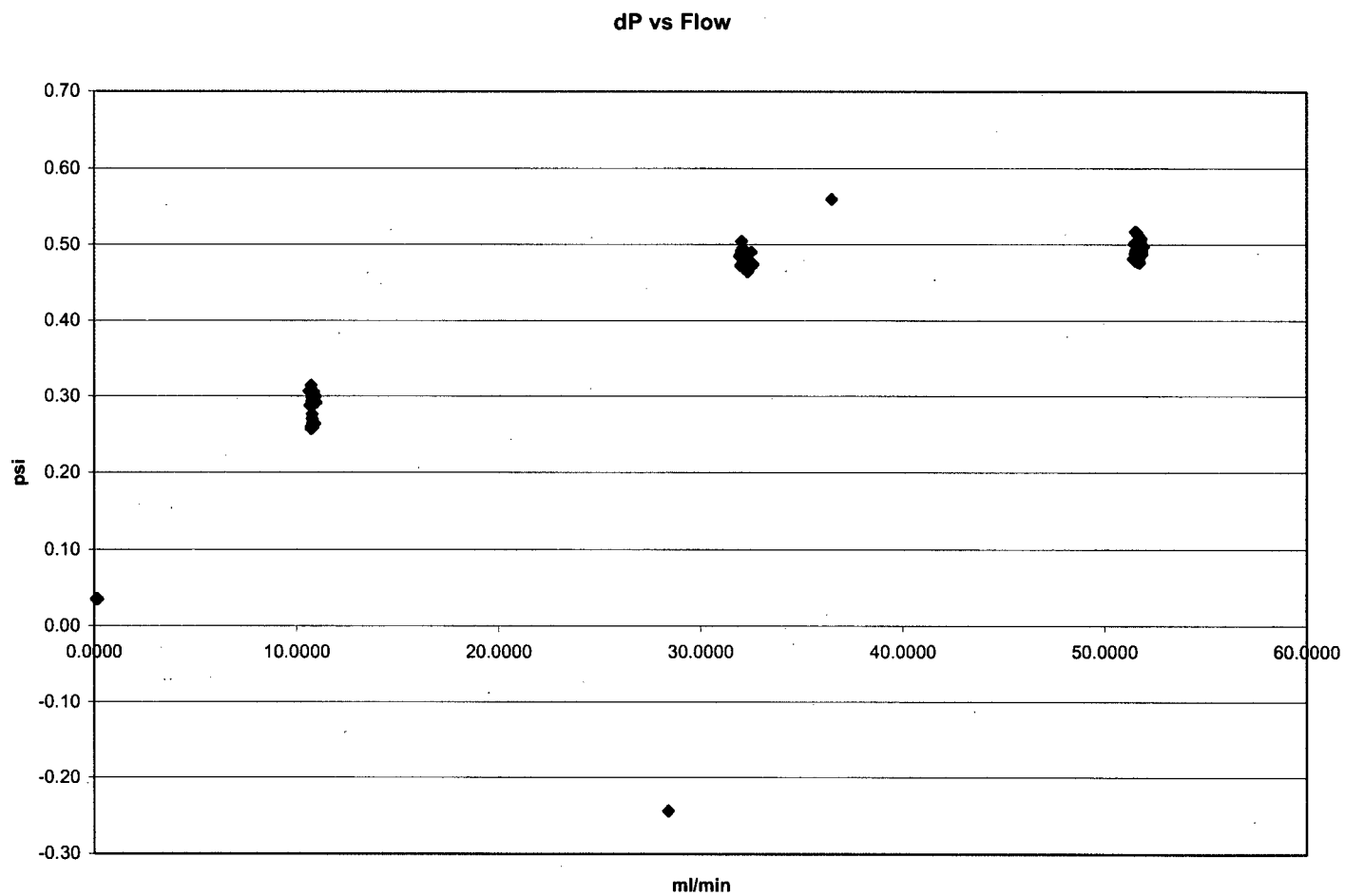


Figure C-15 – dP vs. Flow for PPT35 @ 78°F (12 to 55 ml/min only)

(n = .8737 cP; z = 0.029387816+/- 0.00106635 psi-min/ml)

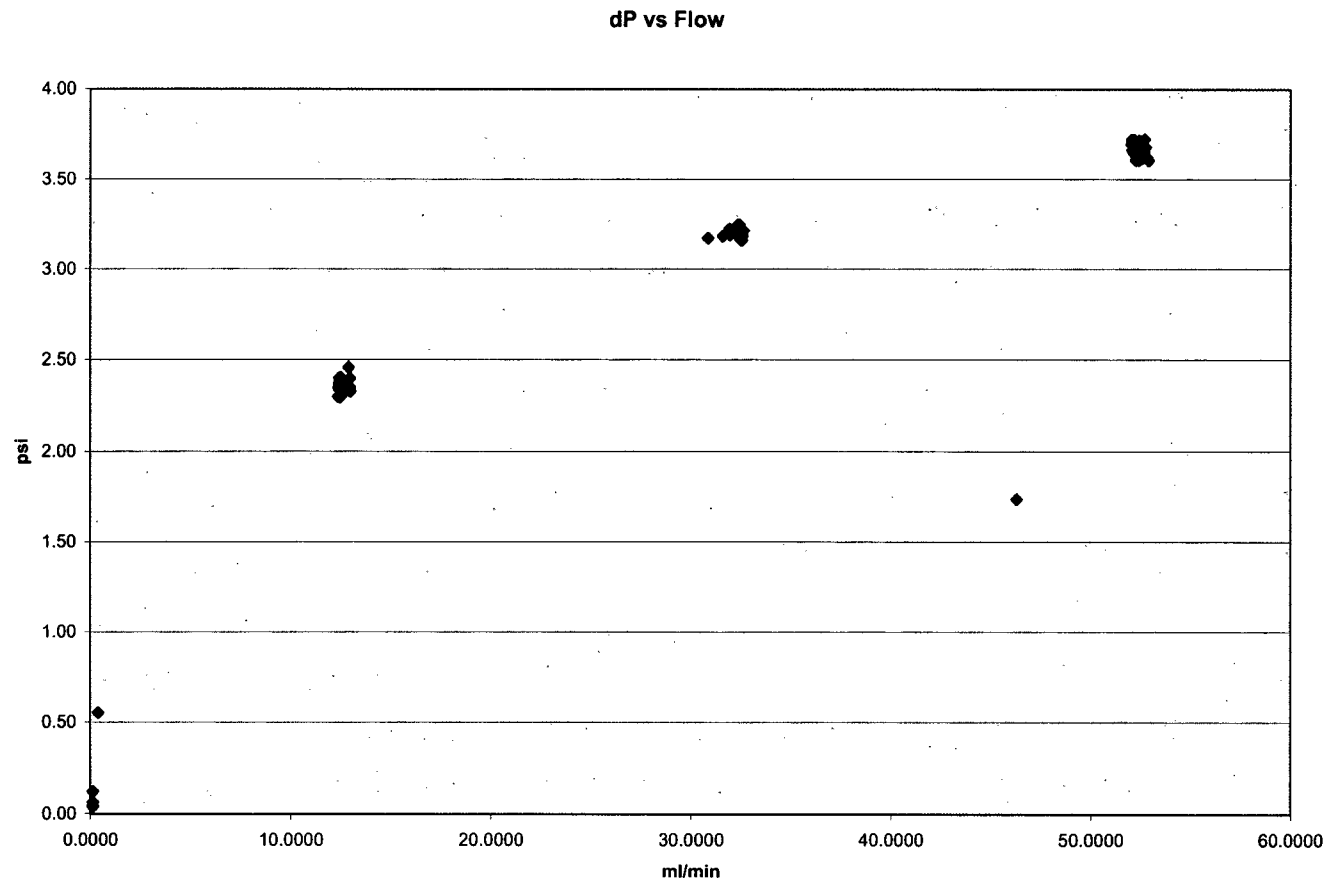


Figure C-16 – dP vs. Flow for PPT38 @ 78°F (0 to 24 ml/min only)

($n = .8737$ cP; $z = 1.082233604 \pm 0.039970312$ psi-min/ml)

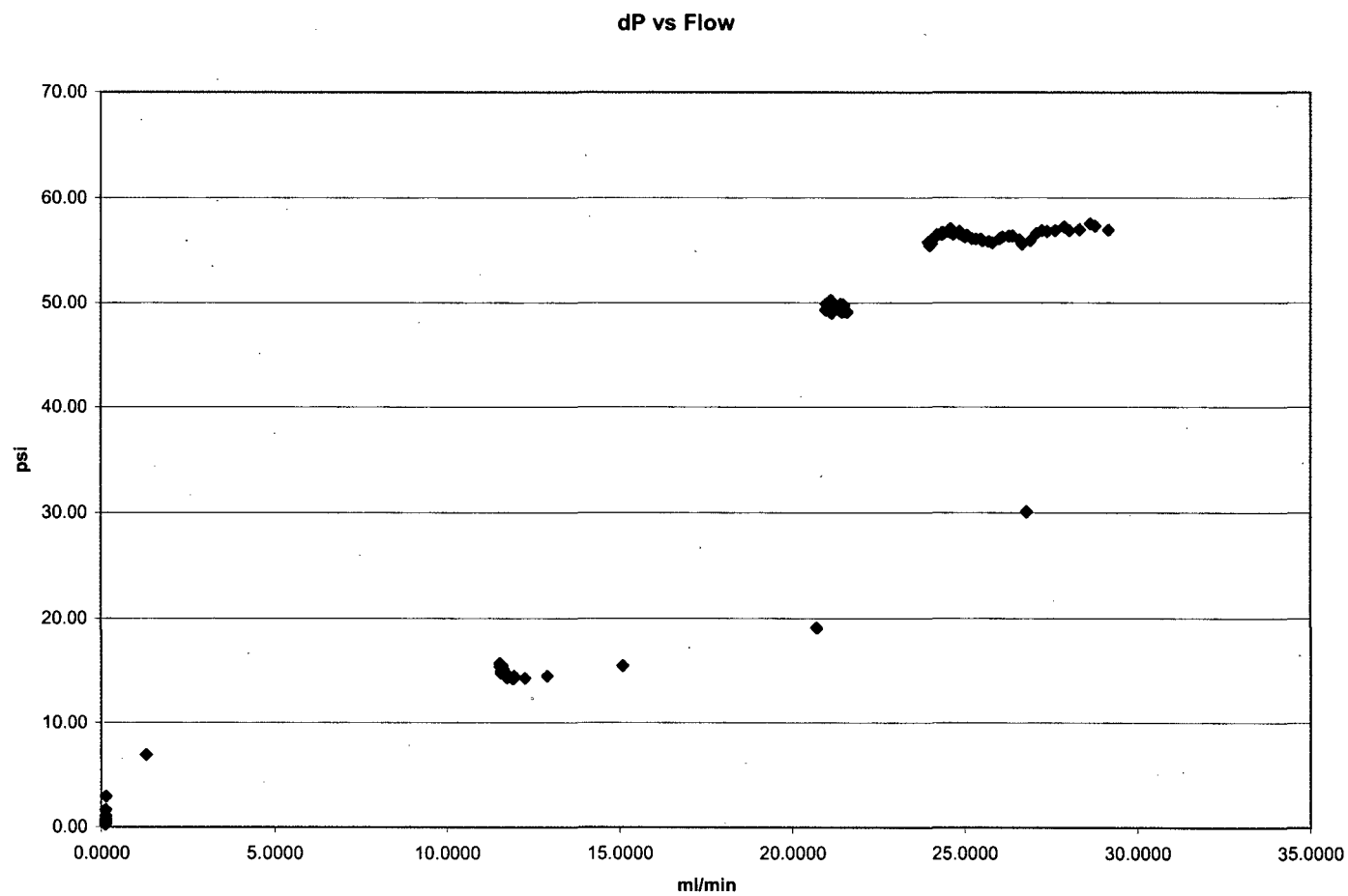
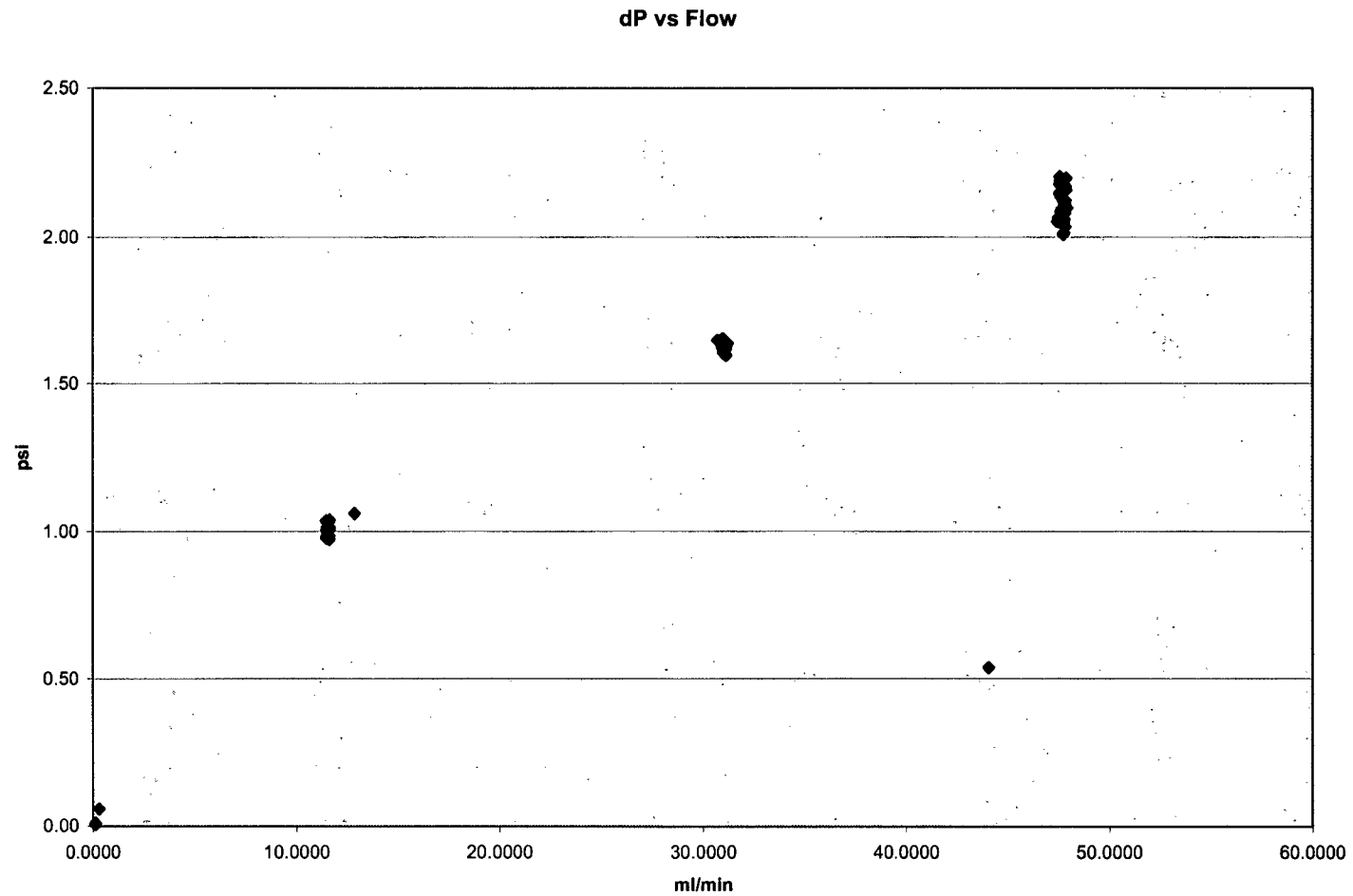


Figure C-17 – dP vs. Flow for PPT60 @ 78°F (15 to 48 ml/min only)

($n = .8737$ cP; $z = 0.030318299 \pm 0.001161737$ psi-min/ml)



APPENDIX D: DETAILS OF CHEMICAL MODEL

This appendix presents the evaluations preformed in the Microsoft Excel file containing the chemical model developed as part of this test program, which is transmitted along with this report. The detailed calculations are provided for validation purposes and to meet internal QA requirements.

Worksheet = Time Temp pH Input

This worksheet is used to enter the time-temperature profiles, including sump and steam temperature, and time-pH profile in containment post-accident.

Column A contains the time in seconds from accident initiation to 30 days over 35 rows. Each row of Column B converts the Column A time to minutes by dividing each row entry by 60 sec/min, while Column C then converts to hours by dividing by 60 min/hr. Finally, Column D converts the time to days by dividing by 24 hr/day.

Columns E and F contain the sump pH and sump temperature values, respectively, at the corresponding times in Columns A-D. Similarly, Columns H and I contain the data for the spray pH and steam temperature.

Column G presents the option to allow the elemental mass already released into the sump solution to impact the dissolution rate from each material containing that element. In order to take credit for this effect on the dissolution rate, the sump solution must be mixed; this is indicated by entering 1 into the rows starting at the time the sump solution is assumed to become mixed.

Note that if data is entered over a different range of cells than is shown in the example, the worksheets referencing this data must all be changed by adding or subtracting rows accordingly. The easiest approach at this time is to adjust the data to fit into example cell range.

Worksheet = Materials Input

This worksheet is used to input the containment material data, such as that requested on the plant survey, and the recirculation water volume. The materials are divided into the material classes determined for testing. Also, there is a flag to indicate whether or not trisodium phosphate is used as a buffering agent.

Column A lists the material classes developed to sort the containment materials by chemical composition. Column B lists the materials within each class. Finally, the amount of each material should be input in Column C using the units listed in Column B. No calculations are performed in this worksheet.

Worksheet = Materials Conversions

This worksheet converts the material amounts input in the previous worksheet to mass for all materials but the aluminum. The mass input in the "Materials Input" worksheet is applied in this worksheet for the aluminum.

Column A, B, and C contain the material class, material, and material amount set equal to those provided in the same columns in the "Materials Input" worksheet for all materials but the submerged aluminum. Column D then contains density values for the recirculation water and the insulation materials in lbm/ft^3 . Column E converts the material volumes to mass (kg) by first multiplying Column C by the density in Column D then dividing by the conversion factor of 2.2046 lbm/kg . The not-submerged aluminum is converted to kg simply by multiplying the Column C mass (lbm) by the conversion factor of 2.2046 lbm/kg . The concrete material amount is input in ft^2 , so Column E multiplies the Column C surface area by $1.0058\text{E-}5 \text{ kg/ft}^2$. This number was obtained as described in Section 6.3 from a surface area analysis performed on the tested concrete.

The submerged aluminum surface area and mass in this worksheet are made up of both the submerged aluminum in the "Materials Input" worksheet and a portion of the Interam volume due to its aluminum foil backing. The aluminum submerged surface area in cell C3 is that provided in the previous worksheet plus the Interam volume divided by the measured aluminum thickness (in) of the test sample which is divided by the conversion factor of 12 in/ft.

$$C3 = \text{Materials Input}!C3 + \text{Materials Input}!C27 / (0.398 \text{ in} / 12 \text{ in/ft})$$

The aluminum submerged mass in cell C4 is that provided in the previous worksheet plus the Interam volume, which is divided by the measured thickness then multiplied by 0.0392 lbm/ft^2 and the conversion factor of 2.2046 lbm/kg to determine the mass of the aluminum foil backing on the Interam in lbm. In order to determine the lbm/ft^2 of the aluminum foil backing, a 1 in^2 piece of the backing was weighed to determine the mass of 0.1234 g. Then the density of this backing is $0.1234 \text{ g/in}^2 * (144 \text{ in}^2/\text{ft}^2) / 1000 \text{ g/kg} * 2.2046 \text{ lbm/kg} = 0.0392 \text{ lbm/ft}^2$.

$$C4 = \text{Materials Input}!C4 + (\text{Materials Input}!C27 / (0.398 / 12)) * 0.0392 * 2.2046$$

Finally, the masses calculated within each class are summed in Column F to provide a class total (kg) for each material class tested.

Worksheet = Results Table

This worksheet sums the elemental mass releases calculated for each material on subsequent worksheets and then predicts the amount and type of precipitates which form from the dissolved elements.

Column C calculates the interval duration, i.e., the time (min) between the inputs provided in the "Time Temp pH" worksheet. Cell C2 is the second time provided in the Time Temp pH worksheet minus that given for the time of RCS blowdown.

$$C2 = \text{Time Temp pH Input}!B3 - \text{Time Temp pH Input}!B2$$

For the next row, cell C3, the interval duration is calculated between the second and third times for which temperature and pH input is given in the Time Temp pH worksheet.

$$C3 = \text{Time Temp pH Input}!B4 - \text{Time Temp pH Input}!B3$$

This calculation is continued until row 34 where the last time for which temperature and pH input is provided is subtracted by the second to last time.

C34 = 'Time Temp pH Input'!B35-'Time Temp pH Input'!B34

In Column D, the start of the interval is simply set equal to the times given in Column C (hr) of the “Time Temp pH” worksheet which correspond to the times subtracted in calculating the interval duration.

The end of the interval (hr) is calculated in Column E by adding the start of interval time (hr) to the interval duration (min) divided by 60 min/hr.

For Column F, the average pH over each interval is calculated by summing the sump pH values corresponding to the times at the start and end of each interval and then dividing that sum by 2.

F2 = 'Time Temp pH Input'!E3-'Time Temp pH Input'!E2 and

F3 = 'Time Temp pH Input'!E4-'Time Temp pH Input'!E3

Similarly, in Column G the average sump temperature over each interval is calculated by summing the sump temperature values corresponding to the times at the start and end of each interval and then dividing that sum by 2.

G2 = 'Time Temp pH Input'!F3-'Time Temp pH Input'!F2 and

G3 = 'Time Temp pH Input'!F4-'Time Temp pH Input'!F3

Then in Column H the corresponding calcium release over time is summed from the Ca releases determined in subsequent worksheets from calcium silicate, concrete, E-glass, and mineral wool.

H2 = SUM('Ca from CalciumSilicate'!S2,'Ca from Concrete'!S2,'Ca from E glass'!S2,'Ca from Mineral Wool'!S2)

The total calcium mass release calculated in row 34 is the sum released over the 30 days.

Similarly in Column I the silicon release over time is summed from the Si releases determined in subsequent worksheets from calcium silicate, concrete, E-glass, aluminum silicate, mineral wool, and Interam.

I2 = SUM('Si from CalciumSilicate'!S2,'Si from Concrete'!S2,'Si from E glass'!S2,'Si from Al Silicate'!S2,'Si from Mineral Wool'!S2,'Si from Interam'!S2)

The total silicon mass release calculated in row 34 is the total Si released over the 30 days.

In Column J the aluminum release over time is summed from the Al releases determined in subsequent worksheets from the unsubmerged aluminum, the submerged aluminum, concrete, E-glass, aluminum

silicate, and mineral wool. The aluminum foil backing on the Interam is accounted for in the submerged aluminum surface area entered.

$J2 = \text{SUM}('A1 \text{ Release by unsubmerged metal}'!U2, 'A1 \text{ Release in Sump from Al}'!U2, 'A1 \text{ from Concrete}'!S2, 'A1 \text{ from E glass}'!S2, 'A1 \text{ from Al Silicate}'!S2, 'A1 \text{ from Mineral Wool}'!S2)$

The total aluminum mass release calculated in row 34 is the total Al released over the 30 days.

Next, the precipitate formation is calculated in Columns K-P from the total mass releases determined in Columns H-J. The equations presented in Section 6.4 to determine the quantity of precipitates generated are used.

In Column K, the amount of sodium aluminum silicate precipitate formed is determined. This column contains an if statement that allows the formation of precipitate to be limited by the amount of aluminum if the mass of dissolved silicon is greater than 3.12 times the mass of dissolved aluminum; otherwise, it is limited by the amount of silicon present.

If the silicon mass is greater than 3.12 times the aluminum mass, Column N calculates the amount of sodium aluminum silicate precipitate by multiplying the Column J aluminum release by 9.72. Otherwise, Column O calculates the precipitate amount by multiplying the Column I silicon release by 3.11.

$K2 = \text{IF}(I2 > 3.12 * J2, N2, O2)$

$N2 = 9.72 * J2$ and $O2 = 3.11 * I2$

The total sodium aluminum silicate precipitate calculated in row 34 is the total precipitate formed over the 30 days.

Column L also contains an if statement, which requires the aluminum release to be at least 0.32 times the silicon release for aluminum oxyhydroxide precipitate to form. If the aluminum release is equal to or greater than 0.32 times the silicon release, then the amount of precipitate formed is 2.22 times the difference between the aluminum release and 0.32 times the silicon release.

$L2 = \text{IF}((J2 - 0.32 * I2) < 0, 0, 2.22 * (J2 - 0.32 * I2))$

The total aluminum oxyhydroxide precipitate calculated in row 34 is the total precipitate formed over the 30 days.

Column M contains an if statement that sets the amount of calcium phosphate precipitate equal to 0 if no amount is entered for trisodium phosphate in the "Materials Input" worksheet, otherwise, the precipitate is the amount calculated in Column P from the calcium release. Column P calculates the amount of calcium phosphate formed due to the presence of trisodium phosphate by multiplying the Column H calcium release by 2.58.

$M2 = \text{IF}('Materials \text{ Input}'!SC\$26=0, 0, P2)$ and $P2 = 2.58 * H2$

The calculations above are continued until the last interval duration in row 34. The total calcium phosphate precipitate calculated in row 34 is the total precipitate formed over the 30 days.

Worksheet = Releases by Material

This worksheet simply sums the elemental releases from each material and presents a column chart with this data.

For example, for the E-glass material, the Ca release in Column B is the sum of the Ca interval mass release calculated in the “Ca from E glass” worksheet.

B6 = SUM('Ca from E glass'!R2:R101)

Worksheet = Precipitate by Material

This worksheet determines the relative contributions of each material to the precipitates formed. In order to determine a material's contribution to a precipitate amount, the total amount of the precipitate is multiplied by the ratio of the mass release of the major element which forms the precipitate from that material to the total release of that element from all materials.

For example, for the amount of the calcium phosphate precipitate which may be attributed to the calcium silicate, the sum of the interval calcium mass release in Column R of the “Ca from Calcium Silicate” worksheet is divided by the sum of the total calcium mass release in Column B of the “Releases by Material” worksheet to obtain the ratio. Then this ratio is multiplied by total calcium phosphate precipitate from cell M34 in the “Results Table” worksheet.

B5 = SUM('Ca from CalciumSilicate'!R2:R100)/SUM('Releases by Material'!\$B\$3:\$B\$20)*'Results Table'!\$M\$34

Worksheet = Ca from Calcium Silicate

This worksheet determines the mass release of calcium over time from the calcium silicate amount input in the “Materials Input” worksheet.

The mass of the material (kg) in cell B2 is set equal to that determined for the calcium silicate class in the “Materials Conversions” worksheet (cell F7). Then the mass of the Ca element (kg) is determined in cell B3 by multiplying the calcium silicate mass by 0.345, the fraction of calcium in the nominal calcium silicate formula. The values input in Column B for the constants a-f are given in Table 6.2-1. Constants a, b, and c are used to determine the saturation constant in Equation 6-3, while the d, e, and f constants are used in Equation 6-4 to determine the rate constant.

Columns C-G are the same as those described for the “Results Table” worksheet.

Column H calculates 1000/temperature (K) from the temperatures in Column G. The temperatures in Column G are first converted to Kelvin and then are divided into 1000.

$$H2 = 1000/((G2-32)*5/9+273.15)$$

Columns I-K allow for the presence of calcium released from other materials to reduce the release rate of calcium from the calcium silicate material as the release rate is dependent on the total concentration of calcium in solution. This credit is only applied if the sump is assumed to be well mixed on the "Time Temp pH Input" worksheet (e.g., approximately two turnovers of the sump volume after recirculation is initiated).

Column I determines the concentration of calcium at the end of the previous time interval from all the materials by dividing the total mass (kg) of calcium released from Column H of the "Results Table" worksheet" by the coolant mass (kg) from Column E of the "Materials Conversions" worksheet. Then this concentration is divided by 1000000 in order to determine the concentration in ppm.

In the initial time interval, the concentration of calcium released from the previous time interval is 0.

$$I2 = 0 \text{ and } I3 = \text{'Results Table'!H2/'Materials Conversions'!E\$2*1000000}$$

Similarly, Column J calculates the concentration of calcium at the end of the previous time interval from the calcium release from calcium silicate calculated in Column S. The total mass of calcium released in Column S is divided by the coolant mass and 1000000.

$$J2 = 0 \text{ and } J3 = \text{S2/'Materials Conversions'!E\$2*1000000}$$

Column K selects whether the concentration of calcium released from all materials or just from the calcium silicate should be used to determine the release rate dependent on whether the option has been selected in Column G of the "Time Temp pH Input" worksheet.

$$K2 = 0 \text{ and } K3 = \text{IF('Time Temp pH Input'!G3=1,'Ca from CalciumSilicate'!I3,'Ca from CalciumSilicate'!J3)}$$

Column L calculates the saturation constant using Equation 6-5 from constants a, b, and c, the average interval pH in Column F, and the 1000/T value from Column H.

$$\text{Saturation constant (K)} = 10^{[a + b(\text{pHa}) + c(1000/T)]} \text{ Equation 6-5}$$

$$L2 = 10^{(\$B\$4 + \$B\$5 * F2 + \$B\$6 * H2)}$$

Column M calculates the rate constant using Equation 6-6 from constants d, e, and f, the average interval pH in Column F, and the 1000/T value from Column H.

$$\text{Rate constant (k)} = 10^{[d + e(\text{pHa}) + f(1000/T)]} \text{ Equation 6-6}$$

$$M2 = 10^{(\$B\$7 + \$B\$8 * F2 + \$B\$9 * H2)}$$

Column N calculates the release rate using Equation 6-4 from the calcium concentration in Column K (ppm), the saturation constant from Column L, and the rate constant determined in Column M.

Release rate (RR) = $kA(1-C/K)$ Equation 6-4

$$N2 = M2 * (1 - K2/L2)$$

Column O determines whether the release rate calculated in Column N is positive and if so sets the positive release rate (mg/kg-min) equal to that calculated value. Otherwise, the release rate is set equal to 0.

$$O2 = IF(N2 > 0, N2, 0)$$

Column P calculates the interval predicted release by multiplying the Column O release rate (mg/kg-min) by the interval duration (min) from Column C and the mass of the calcium silicate (kg) determined in Column F of the "Materials Conversions" worksheet. Then this number is divided by the conversion factor of (1E6 mg/kg) in order to obtain the release in kilograms.

$$P2 = C2 * O2 * 'Materials Conversions'!F7 / 1000000$$

Next, in Column Q the amount above the starting mass of material, i.e., the difference between the mass of material released and the mass of the starting material, is determined. In the first row, row 2, the starting mass of calcium from cell B3 is subtracted from the predicted mass release for the first interval. In the second row, the starting mass of calcium is subtracted from the sum of the predicted second interval mass release and the integral mass release from the first interval calculated in Column S.

$$Q2 = P2 - \$B\$3 \text{ and } Q3 = (S2 + P3) - \$B\$3$$

Column R determines the interval mass (kg) of Ca released from the interval predicted mass release and the difference between the mass released and the mass available. If the mass released is less than the mass available, then the interval mass release of Ca is set equal to that calculated in Column P. However, if in an interval more mass is released than is available, i.e., the difference in Column Q is positive, the interval mass released is set equal to the predicted mass release in that interval less the amount of mass predicted to be released above the starting mass.

$$R2 = IF(Q2 < 0, P2, P2 - Q2)$$

Finally, in Column S the integral mass release (kg) is determined. For the first interval, the integral mass released is simply set equal to that calculated in Column R for the interval mass release. Beginning with the second interval, the integral mass released is that released in that interval (from Column R) plus the integral mass released determined for the previous interval (from Column S).

$$S2 = R2 \text{ and } S3 = R3 + S2$$

The above calculations are continued until the last interval duration in row 34. The integral mass release calculated in row 34 is the total mass release of Ca (kg) over the 30 day period.

Remaining Worksheets for Insulation Materials

In the remaining worksheets, the same equations are used to determine the Al, Si, and Ca mass releases as in the worksheet for the calcium mass release from calcium silicate. The only differences are in cell B2 which is set equal to the mass of the respective insulation material calculated in the "Materials Conversions" worksheet, cell B3 which multiplies the material mass by the fraction of the element in the nominal material formula, and cells B4-B9 which provide the saturation and rate constants a-f given in Table 6.2-3. However, for concrete cell B3 is set equal to a large number (1000000 kg) because there is no limit to the mass of the exposed concrete surface area.

The worksheets used to determine the aluminum release from the aluminum metal in containment differ from the other insulation materials because a different corrosion model is used.

Worksheet = Al Release in Sump from Al

For the aluminum submerged in the sump, Columns C-H contain the same equations as described in Worksheet = Ca from Calcium Silicate.

Column J squares the pHa value calculated in Column F.

$$J2 = F2 * F2$$

Column K divides the pHa value in Column F by the 1000/T value in Column H.

$$K2 = F2 / H2$$

In Column P the log prediction of the aluminum release rate is calculated using the model terms A-E from Columns V and W in Equation 6-2, the Column F pHa values, the Column H 1000/T values, the Column J squared pHa values, and the Column K pHa/(1000/T) values.

$$\text{Release Rate (RR)} = 10^{[A + C(1000/T) + D(\text{pHa})^2 + E(\text{pHa})(T/1000)]} \text{ Equation 6-2}$$

$$P2 = \$W\$2 + \$W\$3 * F2 + \$W\$4 * H2 + \$W\$5 * J2 + \$W\$6 * K2$$

Then in Column Q the corrosion rate (mg/m²-min) is calculated from the term in Column P.

$$Q2 = 10^{P2}$$

Column R calculates the interval release by multiplying the Column Q release rate (mg/m²-min) by the interval duration (min) from Column C and the mass of the submerged aluminum (lbm) determined in Column C of the "Materials Conversions" worksheet. Then this number is divided by the conversion factor of 10.7639 lbm/m² in order to obtain the release in milligrams.

$$R2 = Q2 * C2 * \text{'Materials Conversions'!}\$C\$3 / 10.7639$$

Column S determines the interval Al release in kilograms by dividing Column R by 1000000 mg/kg.

$$S2 = R2/1000000$$

In Column T the integral mass release (kg) is determined. For the first interval, the integral mass released is simply set equal to that calculated in Column S for the interval mass release. Beginning with the second interval, the integral mass released is that released in that interval (from Column S) plus the integral mass released determined for the previous interval (from Column T).

$$T2 = S2 \text{ and } T3 = S3 + T2$$

Finally, in Column U the integral aluminum mass release is limited to the mass available. If the integral mass release calculated in Column T is less than the total submerged aluminum mass determined in the “Materials Conversions” worksheet, then the mass available integral mass release in Column U is set equal to that calculated in Column T. Otherwise, the Column U mass release is set equal to the total mass available for release.

$$U2 = \text{IF}(T2 < \text{'Materials Conversions'!}\$E\$4, T2, \text{'Materials Conversions'!}\$E\$4)$$

The above calculations continue until the last interval duration in row 34. The integral mass release calculated in cell U34 is the total mass release of Al (kg) from the submerged aluminum over the 30 day period.

Worksheet = Al Release by Unsubmerged Metal

For the aluminum exposed to the spray, Columns C-H contain the same equations as described in Worksheet = Ca from Calcium Silicate except the average pH and average temperature are determined from the pH and temperature profiles input in the “Time Temp pH” worksheet for the spray solution instead of for the sump.

The remaining columns are the same as those described in Worksheet = Al Release in Sump from Al except for Column R.

Column R calculates the interval release if a spray pH value is entered in Column H of the “Time Temp pH Input” worksheet. Otherwise, the interval release is 0 because the containment spray has been terminated. The interval release is determined by multiplying the Column Q release rate ($\text{mg/m}^2\text{-min}$) by the interval duration (min) from Column C and the mass of the submerged aluminum (lbm) determined in Column C of the “Materials Conversions” worksheet. Then this number is divided by the conversion factor of 10.7639 lbm/m^2 in order to obtain the release in milligrams.

$$R2 = \text{IF}(\text{'Time Temp pH Input'!H3} > 0, Q2 * C2 * \text{'Materials Input'!}\$C\$5 / 10.7639, 0)$$

The above calculations continue until the last interval duration in row 34. The integral mass release calculated in cell U34 is the total mass release of Al (kg) from the unsubmerged aluminum exposed to the containment spray over the 30 day period.

Worksheet = All Aluminum Release with Plot

This worksheet compares the aluminum release over time from the submerged aluminum and the aluminum exposed to the spray.

Column C is set equal to the end of the time duration in Column E of the "Al Release in Sump from Al" worksheet.

$C2 = 'Al\ Release\ in\ Sump\ from\ Al'!E2$

Column B converts this time into minutes by multiplying by 60 min/hr.

$B2 = C2 * 60$

Column D is set equal to the integral aluminum release from the submerged aluminum.

$D2 = 'Al\ Release\ in\ Sump\ from\ Al'!U2$

Column E is set equal to the integral aluminum release from the aluminum exposed to the spray.

$E2 = 'Al\ Release\ by\ unsubmerged\ metal'!U2$

Column F calculates the total aluminum release by summing the aluminum submerged release in Column D and the unsubmerged aluminum release in Column E.

$F2 = D2 + E2$

Finally, the values in Columns D-F are plotted against the time in Column C.

SECTION C



November 21, 2006

OG-06-387

Document Control Desk
U. S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Pressurized Water Reactor Owners Group
Responses to the NRC Request for Additional Information (RAI) on
WCAP-16530, "Evaluation of Chemical Effects in Containment Sump
Fluids to Support GSI-191"

References:

1. PWROG Letter, F. Schiffley to Document Control Desk, "Submittal of WCAP-16530-NP," Evaluation of Post Accident Chemical Effects in Containment Sump Fluids to Support GSI-191" for formal review," WOG-06-113, March 27, 2006.
2. NRC letter from Sean E. Peters of NRR to Gordon Bischoff of PWROG dated October 4, 2006, "Request For Additional Information Re: Westinghouse Owners Group (WOG) Topical Report WCAP-16530-NP, 'Evaluation of Post Accident Chemical Effects in Containment Sump Fluids to Support GSI-191' (TAC NO. MD1119)."
3. WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February 2006.

In March 2006, the Pressurized Water Reactor Owners Group (PWROG) submitted WCAP-16530-NP (Non-Proprietary), Rev. 0, "Evaluation of Chemical Effects in Containment Sump Fluids to Support GSI-191," for review and approval (Reference 1). In October 2006, the NRC provided the formal Request for Additional Information (RAI) (Reference 2) for WCAP-16530 (Reference 3).

Attachment 1 to this letter provides the RAI responses to the 50 questions received in Reference 2. Attachment 2 presents the revised Section 5.4 from Reference 3 based on the RAI responses. Also included on the enclosed CD are the following documents referenced in the RAI responses:

- RAI #12: References 8-10 and relevant pages from References 11-13
- RAI #14: Relevant pages from Reference 1
- RAI #50: Revised chemical model spreadsheet developed per Reference 3

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Taiwan Power Co.
Maanshan 1 & 2

These RAI responses and the revised WCAP section are being provided to support issuance of the draft Safety Evaluation on WCAP-16530.

If you have any questions concerning this matter, please feel free to call Reginald Dulaney at 412-374-6549.

Sincerely yours,

Reginald Dulaney approving for T. Schiffley
Electronically Approved Records Are Authenticated
in the Electronic Document Management System

Frederick P. "Ted" Schiffley, II, Chairman
Pressurized Water Reactor Owners Group

FPS:RRD:mjl

Attachments: 1. RAI Responses
2. Revision of Section 5.4

Enclosure on CD: 1. Chemical Effects Spreadsheet
2. Excerpts from References 8-13 from RAI #12 response
3. Excerpt from Reference 1 from RAI #14 response

cc: Systems and Equipment Engineering Subcommittee
Steering Committee
S. Peters, NRC
W. Rinkacs, Westinghouse
A. Lane, Westinghouse

OG-06-387 Attachments

TAC No. MD1119

**Response to NRC Request for Additional Information on
WCAP-16530-NP, Rev. 0, “Evaluation of Post-Accident
Chemical Effects in Containment Sump Fluids to Support
GSI-191”**

November 20, 2006

Attachment 1**RAI #1**

Dissolution testing was performed with small volume reaction vessels. Please identify the fluid volume in these tests.

RAI #1 Response

The stainless steel reactors were filled to a nominal 150 ml, while the Teflon vessels were filled to a nominal 120 ml.

RAI #2

Given the small sample sizes tested, is it possible that some test samples (e.g., insulation material) would not be representative of the bulk material? For example, could the amount of binder present in an insulation sample vary significantly depending on the sample location? Was any quantitative analysis performed on multiple samples obtained from the non-metallic materials to assure the tested samples were representative?

RAI #2 Response

All potentially non-homogeneous materials (e.g., insulation and concrete) were ground or otherwise treated to produce small particles for testing. Testing of materials in this condition reduces the effects of non-homogeneity inherent in the material. Based on the consistency of the results of test runs performed at different pH and temperature conditions, there is a high degree of confidence that individual test samples were representative. On this basis, a specific analysis to verify homogeneity was not warranted.

RAI #3

Testing was performed using a closed system at elevated temperatures and the reaction vessels were evacuated to aid the introduction of test fluid. Therefore, the air volume to water volume ratio does not appear to be representative of plant conditions. Discuss how more representative levels of carbon dioxide could affect the amount of precipitate (e.g., by formation of carbonates).

RAI #3 Response

The closed-vessel tests were performed to determine dissolution rates of materials. For metals, the presence of higher levels of carbon dioxide could potentially reduce corrosion due to formation of protective metal carbonates. Thus, performance of the material release determinations in a carbon-dioxide depleted atmosphere is conservative.

Following the dissolution exposure, the liquids in the test vessels were transferred to settling cones to test for the formation of precipitates. The solutions were exposed to carbon dioxide from the air for 24 hours during the precipitation tests. Thus, reaction with atmospheric carbon dioxide to form metal carbonate precipitates was possible.

Regarding the potential effect of atmospheric carbon dioxide on the total quantity of precipitates formed, it is important to note that the chemical model assumes that all dissolved aluminum precipitates either as sodium aluminum silicate or aluminum oxyhydroxide. Any aluminum that precipitated as a carbonate would not be available to precipitate as a silicate or oxyhydroxide. Thus, there is no net effect on precipitate quantity in not considering precipitation of carbonates. In addition, aluminum carbonate

would have better filtration characteristics than the silicate or oxyhydroxide. Thus, not considering precipitation of carbonates in the model is conservative.

RAI #4

Sample preparation for energy dispersive spectroscopy (EDS) analysis provided a source of carbon that would mask carbon present in precipitates from other sources, such as organics or carbonates. Discuss whether alternate analytical tests (or alternate sample preparation techniques for EDS analysis) should be performed to permit reliable detection of carbon in the test materials and chemical precipitates.

RAI #4 Response

The exact composition of the precipitates is not as important as their filterability and settling characteristics, so measuring carbon content in the precipitates is not considered to be critical.

RAI #5

Page 37 of the TR states that dissolution rates measured for each containment material are expected to be higher than that obtained from containment material mixtures. The TR further states that trisodium phosphate (TSP) may inhibit the dissolution of calcium silicate. Because calcium levels can reach saturation very quickly, pure dissolution tests with no additions of TSP can provide an underestimate of the amount of calcium silicate that can dissolve and precipitate in an environment buffered with TSP. The presence of phosphate (from TSP) can react with dissolved calcium to form calcium phosphate precipitate thereby removing calcium from solution promoting additional dissolution of calcium silicate. Provide the basis for the statement that TSP may inhibit the dissolution of calcium silicate.

RAI #5 Response

Although the original test plan included in the WCAP or Topical Report (TR) proposed that the presence of TSP may inhibit the dissolution of Cal-Sil, conservatively, no testing was performed to take credit for this effect. As a result, the chemical model typically predicts that all of the calcium silicate insulation is dissolved and available to form precipitate.

RAI #6

Dissolution testing and precipitation testing (Tables 4.2-1 and 4.2-2) evaluated sodium hydroxide (NaOH) environments at pH 8 and pH 12. The pH, however, can strongly influence the amount and form of precipitation products and many plants with NaOH are postulated to have post-loss of coolant accident (LOCA) containment pool pH in the range of 9 to 10. Why were no tests performed to evaluate this pH range?

RAI #6 Response

The test plan was developed with the intention of bounding the possible range of containment sump pH values in US PWRs. A survey was conducted of the plant conditions prior to finalizing the test plan. Fifteen (15) plants reported a pH greater than or equal to 10.0, so a pH of 12 was chosen to bound the data provided. The dissolution tests were performed at pH values across the entire range, so the model is applicable for plants with a pH between 4 and 12.

RAI #7

Describe the sample preparation for non-metallic materials (e.g., NUKON, high density fiberglass, Interam). With the exception of those samples that were crushed, were all other non-metallic materials shredded? What method was used to shred the materials and is the size produced representative of what would occur during a LOCA? Were any processed beyond shredding? (e.g., placed in a blender).

RAI #7 Response

The standard approach that the vendor Performance Contracting Incorporated (PCI) uses for sample preparation is to cut the fibrous insulation into strips and feed them into a wood chipper/shredder. This process yields a combination of fines and small clumps and is consistent with the method generally accepted and used previously in both NRC-sponsored sump performance tests as well as testing performed for BWR and PWR sump performance issues.

RAI #8

According to Section 5.1.2.1 of the TR, some insulation material (i.e., NUKON) was baked, some materials (e.g., mineral wool, high density fiberglass) were not baked, and it is not clear if other materials (e.g., Interam, calcium-silicate) were baked. Provide the thermal history (time and temperature) for all the test materials and a rationale as to why some were thermally treated and others were not.

RAI #8 Response

The primary rationale used in the preparation of materials for testing was to maintain general consistency with the approach taken in the ICET program and to achieve realistic and conservative results.

The purpose of "baking" fiberglass insulation would be to remove organic binders present in the manufactured insulation that could decompose at high temperature under service conditions. Although the quantity of such binding agents is low (<5%), there is some potential that the binding agents could alter the dissolution behavior of the base material. For materials in containment, it is not expected that all of the binding agents in all insulation materials would be lost due to decomposition. Thus, it is not strictly realistic to use either all baked or all unbaked material.

To evaluate the potential effects of binders on dissolution behavior, samples of both unheated fiberglass and heat treated NUKON fiberglass were used during testing. The result of this testing showed material release was comparable/slightly higher from the untreated fiberglass material. On this basis, it is judged that the use of non-heat treated specimens is the preferred method.

NUKON fiberglass was heat treated at 450°F prior to testing. No other materials were heat treated. It may be noted that a high degree of dissolution was measured for non-heat treated CalSil insulation and Min-K samples, consistent with results obtained in the ICET program. These results provide further confidence that use of non-heat treated materials for dissolution testing provides good results.

RAI #9

The TR indicates that (unbaked) high density fiberglass had a larger mass release than baked Nukon fiberglass. Given the short duration of these bench top tests, were any direct comparison (i.e., the same material baked and not baked) tests performed to evaluate how baking could affect the amount and composition of elements released during dissolution testing?

RAI #9 Response

No direct comparisons tests were performed using the same material in a baked and unbaked condition. The "baking" variable was not fully explored since it was considered to be less important than the primary variables of pH, temperature, and base material. Excluding the baking variable from the study is supported by the following:

- 1) Report NUREG/CR-6885 LA-UR-04-5416, page 10, states that organic binder is removed from fibrous insulation after a short exposure to water at temperatures greater than 90°C (194°F). This was demonstrated in the NUREG report for Nukon fiberglass. This should also be the case for the testing done in WCAP-16530, especially in the high pH and high temperature (265°F) tests.
- 2) Microscopic examination indicated that MIN-K, FiberFrax, and Microtherm do not contain binders. Thus, they should not be affected by baking.
- 3) The Interam material is used as a fire barrier, and would not normally be exposed to high temperatures in containment.

The mineral wool material used in WCAP-16530 testing was coated with a binder that did not appear to be readily attacked by the test solutions, which should be consistent with the effect of the post-LOCA sump solution on the material.

RAI #10

Both temperature and pH can affect solubility. It appears from Table 4.2-2, that all pH adjustments in the precipitation test matrix are accomplished by adding TSP or sodium tetraborate (Borax) to the borated, pH 4 environments to raise the pH to 8. None of the pH 12 tests were adjusted to lower pH values. Given that aluminum solubility decreases as the pH is adjusted downward towards 8, would a test with initial higher pH subsequently adjusted to a lower pH be more conservative (i.e., result in more precipitate) than a low pH test buffered to a higher pH? Is it plausible for a containment pool at higher pH (e.g., 9 pH) to move a pH unit or more lower due to formation of nitric or hydrochloric acid after an accident? If so, why was no testing performed by adjusting pH from a higher value to a lower value?

RAI #10 Response

The pH adjustments were made to reflect the large increase in pH achieved in containment by the addition of the sodium tetraborate or TSP buffers. These tests were conducted to observe whether additional chemical precipitates formed due to the interaction of the dissolved materials from the dissolution tests and the newly introduced buffer. The precipitation tests were not used to determine the quantity of chemical precipitate predicted by the chemical model. The chemical model uses the dissolution test results as opposed to the precipitation test results to determine the amount of precipitate formation.

The chemical model uses the measurements of dissolved aluminum from the dissolution testing to predict the quantity of aluminum released. The model then conservatively assumes that all of the aluminum released forms precipitate. Thus, the amount of aluminum precipitate formed is based on the amount of aluminum released not the amount of precipitate observed in the precipitation tests.

RAI #11

Table 3.1-1 summarizes the pressurized water reactor (PWR) survey response concerning containment materials and buffering agents. These results show 55 units with carbon steel and 62 units with concrete.

Since all PWRs contain these materials, one would expect 69 PWR units would report both concrete and steel. Do the survey results indicate the number of units with (and maximum amounts of) carbon steel and concrete that are not coated?

RAI #11 Response

The survey requested the exposed surface area of concrete. The survey also requested the surface area of “uncoated” carbon steel. Therefore, Table 3.1-1 presents the number of units with, and maximum amounts of, uncoated or exposed carbon steel and concrete.

RAI #12

The TR chemical model contains algorithms based on results from the single effects chemical tests. A linear combination of the chemical products from individual test results is used to obtain a total amount of material precipitated. While single effect testing can provide useful information about material behavior, the linear precipitate combination does not consider the possibility of synergistic effects. Given the complexity of the chemical system, that changes to the chemical system have been observed to affect the types and amounts of precipitate and the amount of pressure drop across a debris bed,

(a) justify why dissolution and precipitation tests with material combinations are not needed to evaluate possible synergistic effects

(b) justify why filterability testing should not be performed for combinations of precipitates for comparison to single precipitate tests

RAI #12 Response

a) As discussed below, material interactions were considered in the development of the chemical model and key interactions were included. The synergistic effects of material combinations overwhelmingly tend to reduce material release. Thus, not performing testing on material combinations is conservative. A discussion of key material interactions and how they were addressed in the chemical model is provided below.

Precipitation Reactions

The material interaction of ultimate interest in the Containment Sump Chemical Effects program is combination of dissolved species to create chemical precipitates (solids) that could potentially increase sump screen head loss. Based on the chemical composition of the containment materials and of coolant additives, the predominant classes of precipitates expected would be metal hydroxides/oxyhydroxides, aluminum silicates and metal phosphates (for plants using TSP buffering). Based on the results from the ICET program, WOG testing and NUREG/CR-6873, the specific precipitates expected to predominate would be aluminum oxyhydroxide, sodium aluminum silicate and calcium phosphate¹⁻⁷.

The chemical model assumes that all dissolved aluminum precipitates as either sodium aluminum silicate or aluminum oxyhydroxide. All dissolved silicon is assumed to precipitate as sodium aluminum silicate. For plants using TSP buffering, all calcium is assumed to precipitate as calcium phosphate. The results of the ICET program and other testing⁸⁻¹⁰ showed that some fraction of the dissolved species does not precipitate but remain in solution and do not contribute to the precipitate burden. Thus, the assumption of complete precipitation is conservative.

In practice, some fraction of the available aluminosilicates would precipitate with other cations rather than sodium (e.g., calcium aluminum silicate). However, since all aluminosilicate is accounted for as sodium aluminosilicate, the net effect on total precipitate formation from not including other metal aluminosilicates is zero, discounting the minor differences in molecular weights between the metals.

Also in practice, other metals present in solution may precipitate as phosphates or hydroxides (e.g., zinc phosphate or iron hydroxide). Based on the results of the ICET and the WOG programs, the concentration of other dissolved metals is less than one percent of the concentration of the predominate metals (aluminum and calcium). Thus, the net effect of ignoring these interactions is less than one percent.

Common Ion Effect

For any chemical reaction, the reaction rate is dependent on the concentration of the reacting materials and the resulting products according to LeChatlier's Principle¹¹. As the concentration of the reaction products increases, the reaction slows. This is true independent of whether the reaction product actually comes from the reaction of interest or is introduced from another source. In practice for the dissolution of sump materials, the rate of dissolution is dependent on the concentration of the dissolved species in the sump fluid, irrespective of the source. In cases where an element of interest is released from more than one material, the dissolution rates would be interdependent. For example, calcium may be released from dissolution of calcium silicate, concrete and mineral wools. As a consequence, the release rate of calcium from the individual materials is slower in the presence of the other materials than would be the case if a single material was present. This is true in both the short and long term. The chemical model provides an option to include this effect by accounting for the concentration of each dissolved element from all sources at each time step in the numerical integration.

Loss Due to Precipitation

As a corollary to the common ion effect, the rate of dissolution reactions may increase if a dissolved reaction product combines with other elements or compounds in solution and precipitates as a solid. For example, loss of aluminum due to precipitation as sodium aluminum silicate would tend to increase the dissolution rate of Kaowool and other materials containing aluminum silicate. This effect is not significant during the initial stages of an event when initially rapid material release occurs, and thus there is no net short-term impact from omission of this effect from the model.

Loss due to precipitation would have the largest effect on the dissolution rates of calcium-bearing materials in the presence of trisodium phosphate. Due to the high net release rates for calcium predicted by the chemical model, the net dissolution rate of these materials predicted by the model is in excellent agreement with the results from the ICET program and other published data. Thus, there is no net long-term impact from omission of this effect from the model.

Silicate Inhibition of Corrosion

Silicate is a well-known inhibitor of corrosion of most metals^{12,13}. Silicate inhibition occurs due to formation of insoluble metal silicates on the metal surface. Although there is a significant source of silicate from dissolution of silicate insulation materials, this effect was not included in the generic chemical model. Plants with high silicate loadings may optionally consider inclusion of silicate inhibition if supporting data are available from testing performed outside of the scope of the work reported in WCAP 16530 NP.

Of most concern for sump materials is aluminum corrosion. Omission of silicate inhibition of aluminum corrosion introduces additional conservatism. Note, this effect does not apply for aluminum release due to dissolution of aluminum compounds.

Effects of Dissolved Metals on Corrosion

Dissolved metals such as copper may enhance the rate of corrosion of more active metals due to formation of local galvanic cells on the metal surface¹³. For containment materials, this effect would potentially be most significant for aluminum in the presence of dissolved copper. This galvanic effect would not apply for corrosion of non-submerged aluminum. This mechanism would be expected to be most significant later in the post-accident phase when minor amounts of copper may be present and rapid aluminum corrosion due to extremes in temperature and pH has ceased. However, under these conditions aluminum would be less susceptible to corrosion due to the more neutral pH, lower temperature and the effect silicate inhibition. Additionally, the release rate of more noble metals such as copper is expected to be low under post-accident sump conditions, based on results from the ICET program and literature data¹³. On the basis of the above discussion, the effect of dissolved active metals on corrosion is judged to be insignificant.

References to RAI #12 a) response:

1. LA-UR-05-0124, "Integrated Chemical Effects Test Project: Test #1 Data Report," June 2005.
2. LA-UR-05-6146, "Integrated Chemical Effects Test Project: Test #2 Data Report," September 2005.
3. LA-UR-05-6996, "Integrated Chemical Effects Test Project: Test #3 Data Report," October 2005.
4. LA-UR-05-8735, "Integrated Chemical Effects Test Project: Test #4 Data Report," November 2005.
5. Oras, J., et al., "Chemical Effects/Head Loss Testing Quick Look Report, Tests ICET 3-4 to 11," January 20, 2006.
6. WCAP 16530-NP, Rev. 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February 2006.
7. V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191," NUREG/CR-6873, April 2005.
8. Mattigo, S. V., et al., PNNL Report PNNL-13881, "Precipitation of Aluminum Containing Species in Tank Wastes," April 2002.
9. Bolinger, J-C., et al., "Repartition of Various Soluble and Insoluble Species in Supersaturated Solutions," *Pure and Applied Chemistry*, Vol. 70(10), 1998.
10. Addai-Mensah, J., et al., "Sodium Aluminosilicate Solid Phase Specific Fouling Behavior," *Heat Exchanger Fouling and Cleaning: Fundamentals and Application*, Vol. RP1, Art. 11, Berkeley Electronic Press, 2004.
11. Alberty, R. and Daniels, F., *Physical Chemistry*, Fifth Edition, John Wiley & Sons, 1979.
12. Smallman, R.E. and Bishop, R.J., *Modern Physical Metallurgy and Materials Engineering - Science, Process, Applications (6th Edition)*, Elsevier, 1999.
13. Revie, R. Winston, ed. *Uhlig's Corrosion Handbook* (2nd Edition). John Wiley & Sons, 2000.

b) Filterability tests performed during the test program were conducted to provide a measure of the suitability of the surrogate precipitates, and were not intended to be used to benchmark or to replace testing performed by sump strainer vendors. When applicable, combinations of precipitates have been/will be used in sump strainer testing.

RAI #13

Previous integrated chemical effects testing (ICET) was performed with 100 ppm chloride addition. Page 38 of the WCAP states that hydrochloric acid was not added to these tests since the products of acidic radiolysis are not expected to be significant early in a postulated event prior to completion of buffering agent addition. The TR also states that after addition of the buffering agent, the long term generation of hydrochloric acid will have little effect on pH. However, chlorides could leach from other containment materials (e.g., coatings) and enhance corrosion of metallic materials. Estimate how much chloride could be present in the containment pool and discuss any expected difference in dissolution rates for the metallic coupons in the presence of chloride.

RAI #13 Response

For materials in containment such as coatings, limits are placed on the concentration of leachable chloride and other potentially harmful materials. Thus, a significant source of leachable chloride is not present in containment. This was specifically evaluated during the development of the test protocol for the ICET program, and it was determined that the leachable chloride content of coatings was sufficiently low to justify not considering chloride from this source. Data supporting this determination was previously provided to the NRC during development of the test protocol in the ICET program¹.

Additionally, as noted in the WCAP, metal corrosion rates determined in this program were comparable, and in most cases higher, than results reported in testing in which chloride was intentionally added.

References to RAI 13 Response:

1. This information was transmitted by Martin Murphy, Materials and Chemical Engineering Branch, NRC, to a coatings industry representative, Mr. Jon Cavallo, Vice-president, CCCL, and ASTM D-33 Committee chairman, via a 28 page facsimile transmittal on June 14, 2004. The package of information included data sheets of leaching testing performed for coatings manufactured by both Keeler & Long/PPG Industries and Carboline Company. These data sheets documented the small amount of leachable chlorides in coatings used inside containment.

RAI #14

Potential corrosion products that could be released from the internal surfaces of the reactor coolant system (RCS) during a LOCA are discussed on Page 39 of the TR, which states that based on experience with plant shutdown chemistry, it is considered likely that no more than a small quantity (<5 kilograms) of oxide would be released from the internal surfaces of the RCS. Figure 5.1-1 shows nickel released from the RCS during shutdowns for three-loop and four-loop PWRs. Discussion on Page 46 states that it is expected that the amount of material released during a LOCA would be expected to be similar to that experienced during a normal PWR shutdown. Discuss the mechanism for release of corrosion products during a normal shutdown relative to a LOCA. Given the thermal hydraulic transient associated with a large break LOCA, wouldn't substantially more oxide be released from the internal RCS surfaces compared to a controlled plant shutdown? Provide an estimate for the amount of material (e.g., magnetite, nickel ferrite) that would be released from RCS internal surfaces during a large break LOCA.

RAI #14 Response

Conservative estimates indicate on the order of 189 kilograms of adherent oxides are present within the primary circuit – including fuel surfaces – of a large four-loop plant. Crud build up models have been developed that estimate the fraction of the crud inventory that can be released as particulates due to shear forces and those that can be transported by dissolution followed by precipitation. The estimates of such material ranges between 12 and 25 kilograms¹. This represents the upper bound of what could be released during a large-break LOCA.

Primary system metal oxides are dense (specific gravity from 3.8 to 6.4), and would not readily be transported to the sump screens. Additionally, the oxides would be easily filterable. This judgment is based on experience during primary side chemical decontamination application as well as plant operational experience.

References to RAI 14 Response:

1. Jim Henshaw, John C. McGuire, Howard E Sims, Ann Tuson, Shirley Dickinson, Jeff Deshon "The Chemistry of Fuel Crud Deposits and Its Effect on AOA in PWR Plants, Proceedings of the International Conference on Water Chemistry of Nuclear Reactor Systems, Jeju Island, Korea, October 23-26, 2006. Page 17

RAI #15

The TR chemical model does not consider the release of radioactive species during the LOCA and their subsequent affect on the containment pool chemistry. Among the potential influences of these species are:

- (a) contribution of additional particulate loading
- (b) radiolysis of water within the containment pool that could modify the reduction potential (i.e., redox potential) of the water depending on the relative amounts of H₂, O₂, and H₂O₂ produced. This could potentially affect corrosion rates, chemical speciation, and the solubility of compounds.
- (c) possible alteration of a debris bed, if radioactive species were transported to and concentrated within a bed to produce locally oxidizing conditions that could increase the probability of precipitation or co-precipitation of oxides
- (d) effect of radiolysis on materials that comprise the debris bed and the ability to break down into more soluble components that may subsequently precipitate.

Please discuss potential influences from the presence of radioactive species in the containment pool including any data that may provide insight into the potential influences described above.

RAI #15 Response

As discussed in the response to item 14, it is anticipated that oxides released from the primary surfaces would quickly settle due to their high density. Thus, there would be little direct contact with structural materials such as insulation.

Inorganic containment materials (e.g., metals and insulation materials) are predominantly resistant to break down by radiolysis. For example, silicate materials similar to insulation are present in CRUD on the core. Thus, the effect of direct contact by high specific activity oxides would be negligible. For example, borosilicate material, which is chemically similar to fiberglass, is routinely used as a filtration media for high activity particulate.

Although no direct data are available, it is not expected that the presence of highly oxidizing free radicals would strongly affect the dissolution of inorganic containment materials such as insulation since the dissolution does not occur by oxidation. As with possible radiolysis effects, it should be recognized that similar materials (e.g., calcium and aluminum silicates) are present in CRUD and would be subject to high concentrations of free radicals generated from radiolysis of water.

RAI #16

The concrete used in bench top testing was ground and aged for 28 days prior to use. This concrete was supplied by Performance Contracting Inc. Please provide the composition and applicable specifications for the concrete tested. Was the concrete tested representative of concrete in the U.S. PWR plants? Given the variability in concrete composition in the various regions where nuclear plants are constructed,

- (a) discuss whether these test results are sufficient to represent industry wide concrete dissolution and precipitation.
- (b) discuss how variability in concrete composition may affect the output from the chemical model for a plant with a large area of uncoated concrete.

RAI #16 Response

a) Variations in the concrete used at different sites could include differences in the relative percentages of sand, gravel, etc. and cement used to prepare the concrete, as well as environmental conditions during curing (e.g., use of ice to reduce the curing exotherm). However, such variations do not have a significant effect on the base chemical constituents. That is, concrete is predominantly silicon dioxide (from sand, gravel, etc.) and calcium silicates, with minor amounts of other metal silicates (i.e., cement). Changes to the recipe and curing process do not affect this base composition. On this basis, the dissolution behavior of concrete is expected to be consistent between sites.

b) As noted above, variability in concrete composition would have a negligible effect on the model output for uncoated concrete. It is further noted that the material release from concrete (predominantly calcium and silica) per unit surface area is quite low, and concrete is not a major contributor to the overall precipitate burden.

RAI #17

Table 5.1-3 shows normalized (oxygen and carbon removed) compositions of the test materials. Based on the reported EDS results, the staff has several questions:

- (a) The reported sulfur content is much greater than allowed in the SA 508, Class 2 material specification. Is there an additional source of sulfur in the analyzed sample or is the reported amount resulting from interference between sulfur and other elements (e.g., molybdenum X-ray wavelength overlap with sulfur)?

(b) For the SA 508 sample composition, what is the source of the aluminum? Is the reported aluminum a result of electron beam interaction with other aluminum containing materials in the Scanning Electron Microscopy (SEM) vacuum chamber? If so, what are the ramifications for the reported aluminum analyses of the other test materials or for the precipitate analyses?

RAI #17 Response

a) The “sulfur” reported in SA 508 was actually not present. As was suggested in the RAI, the signal attributed to sulfur was actually molybdenum which is a component of the alloy.

b) The aluminum signal originates from other aluminum containing materials in the vacuum chamber, but the signal was small (1.5% in the case of the steel). This should not affect the chemical model or the conclusions of the report since the aluminum content of the precipitates was not used in modeling. The total aluminum release measured by ICP analysis was the parameter that was used to predict the amount of precipitate generated by post-LOCA chemical reactions.

RAI #18

Table 5.1-4 presents the amount of material used in the dissolution tests. On Page 61, the TR states that the target ratios were the maximum ratios from Table 3.1-1 reported in the industry survey. The values in Table 5.1-4 appear to be consistent with the values shown in Table 3.1-1, with the exception of fiberglass. The maximum fiberglass insulation/coolant ratio listed in Table 5.1-4 is $0.14 \text{ ft}^3/\text{ft}^3$. The maximum fiberglass to recirculation water volume ratio shown in Table 3.1-1 is $0.23 \text{ ft}^3/\text{ft}^3$. Please clarify the discrepancy and discuss if this affects the chemical model.

RAI #18 Response

At the start of the testing, not all of the plant surveys had been received and reviewed. The maximum fiberglass insulation/coolant ratio of $0.14 \text{ ft}^3/\text{ft}^3$ used in testing was based on the survey data available at the time the test protocol was developed. In reviewing the complete survey responses, only two (2) units have fiberglass to recirculation water volume ratios greater than $0.14 \text{ ft}^3/\text{ft}^3$, at 0.18 and $0.23 \text{ ft}^3/\text{ft}^3$.

Although the stated intent of the bench tests was to use the maximum observed volume ratio for the individual components, the release rate equations are based on the total mass of insulation present, rather than the volume ratio. There is no technical basis or data to suggest that a higher release rate per unit mass would have been obtained if a higher volume ratio sample was used in the test runs. On this basis, there is no effect on the validity of the resulting chemical model and no changes are necessary.

RAI #19

Section 5.2.3 indicates a total of 88 bench top tests were accepted and of these 22 tests were considered as replicate tests. Describe the amount of variability observed in the replicate tests and discuss how the results from the replicate tests are factored into the chemical model? Was there a stated data quality objective for these tests with respect to repeatability? If not, why not?

RAI #19 Response

The results from the replicate tests were included in the regressions used to formulate the chemical model. Inspection of the repeat runs in Table A1 shows that the run-to-run variability was high, with individual values sometimes varying by more than 50%. There was no acceptance criterion for repeatability since

large run-to-run variations were expected and were thought to reflect real-world variations that would occur between different LOCA events.

RAI #20

At the completion of the dissolution tests, were the remaining samples and the filter examined (e.g., by using a stereoscope, scanning electron microscope) to look for evidence of deposits or chemical products within the non-metallic samples or on the filter? If so, provide results from these examinations. If not analyzed with microscopy, indicate why this was not done.

RAI #20 Response

The samples and filters were not routinely examined microscopically, but were examined visually. There was no visible evidence precipitates formed within the materials or in the vessels during the high temperature tests (190°F and 265°F). The primary focus of the project was to determine release rates of dissolved species from the materials to quantify precipitate formation as a function of chemistry and temperature conditions, and to develop techniques to generate prototypical precipitates. It is not considered likely that precipitates would have formed in the vessel and not have been subsequently observed in the test solution when it was transferred out of the test vessel.

RAI #21

The precipitation test matrix shown in Table 5.2-3 indicates that the precipitation of phosphates with calcium silicate (PPT run #35) was tested by buffering the dissolution run #7 with trisodium phosphate. Dissolution run #7 was performed at 265°F. Given that more calcium is dissolved from calcium silicate at 190°F than at 265°F, would more calcium phosphate have precipitated in PPT run #35 if a dissolution run at 190°F had been used? Please discuss how the chemical model uses the data from different temperatures to determine the release rate of calcium from calcium silicate insulation.

RAI #21 Response

More calcium was released in the lower temperature dissolution runs, so more calcium phosphate precipitate would have formed if TSP was added to the 190°F calcium silicate dissolution run. However, the amount of precipitation predicted by the chemical model is not dependent on the quantity of precipitate observed in the precipitation runs. The amount of calcium released in each dissolution run was measured using ICP analysis, and subsequently, a release rate equation was developed from this data. The release rate equations were based on the data from dissolution runs at both temperatures: 190°F and 265°F.

RAI #22

The apparatus in Figure 5.2-15 was used to measure the mass of precipitate settled. The cones used in this test are standard cones used for testing sub-micron particulate matter in fuel oil using a high speed centrifuge. The chemical precipitates generated during TR testing would have different sizes and hydration spheres from the material assumed in the fuel oil test. Explain how the settling characteristics of the chemical precipitates would not be affected by the settling cone shape and dimensions.

RAI #22 Response

The settling tests were used to observe the general settling characteristics of the precipitates and to make relative comparisons between the types of chemical precipitates and surrogates. The settling

characteristics of each chemical precipitate would be affected similarly by the settling cone shape and dimensions, supporting a relative comparison of their settling behavior.

RAI #23

The coefficients provided for the aluminum release in Equation 6-1 (Page 93) appear to be incorrect. Please provide corrected values for this equation.

RAI #23 Response

The value for the “B” coefficient should have been -0.4371 rather than 0.4371 (sign error). Otherwise, the coefficients are correct. It should be noted that Equation 6-1 was not used in the chemical model. It should also be noted that Equation 6.1 was derived only from the release rate data calculated from solution concentrations (Run E5-1, C5-1, Q7-1, D5-1, K7-1, N7-1, S7-1). Equation 6.2 and Table 6.2-1 included both the release rate data from the solution concentrations and the release rate measurements based on coupon weight loss. The weight loss data and the solution concentration data were averaged.

RAI #24

Table 6.2-1 provides an average aluminum corrosion rate for the ICET 1 coupons equal to 12.2 mg/m²-min. Please describe how this rate was calculated. If it was calculated from coupon weight loss measurements, indicate how corrosion product remaining on the coupons was considered since the coupons were not cleaned before post-test weighing. How does the corrosion rate shown above compare to a rate calculated based on using the measured ICET dissolved aluminum concentrations during the first 10 days of ICET 1 (i.e., 25 mg/l/day)?

RAI #24 Response

The releases calculated from the coupon mass loss were averaged. It was determined to be appropriate not to rinse the compounds since such adherent corrosion products will not be transported to the sump.

It is difficult to compare the dissolved aluminum values and corrosion since there is no way to conclusively determine the quantity of aluminum released that either remains on the coupons as an oxide or oxyhydroxide, or that is released and subsequently precipitates and is thus not measured as “dissolved” aluminum. If one makes the following assumptions:

- all aluminum released is present as dissolved aluminum
- only aluminum released from submerged specimens contributes
- the total submerged coupon surface area was 6 ft² (0.56 m²)
- the system volume was 949 liters,

then the 25 mg/l/day solution concentration increase corresponds to an area based corrosion rate of 29.6 mg/m²/min.

RAI #25

For aluminum release rate, the TR chemical model uses Equation 6-2, developed from fitting several aluminum corrosion data sets. The TR indicates that the fit to this data is poorer than the fit to the aluminum bench test data alone. Given that aluminum corrosion rates increase with increasing pH, the corrosion rate of most interest is associated with environments with pH values greater than 8. For

example, for plants with sodium hydroxide, aluminum corrosion rates in initial high pH containment spray and in equilibrium containment pool pH conditions are most important. Is there an alternate to Equation 6-2, such as a corrected Equation 6-1, or other alternate, that would provide a better data fit in the pH range of most interest?

RAI #25 Response

One set of data did not correspond well with the remaining data, but was included because the intention was to use all available data. An inspection of the fit of the model to the data suggested that these points did not have a significant effect on the model coefficients.

RAI #26

Discuss the basis for the maximum pH (i.e., pH 12) that could occur in containment spray fluid for plants using sodium hydroxide. Is it possible for the spray system pH to reach these values? Were these maximum plant pH values determined based on calculations that used plant-specific values or with calculations that used conservative assumptions? If the pH of 12 was used for conservatism, demonstrate how this would be conservative.

RAI #26 Response

Refer to the response to RAI #6. A pH of 12 was chosen in the development of the test plan to bound anticipated survey responses. The maximum pH is determined by individual plant analyses and was communicated to the PWROG on the plant survey responses. A review of the completed survey responses illustrated that fifteen (15) plants reported a sump pH greater than or equal to 10.0, which provides a good basis for use of a bounding pH of 12 to represent either the sump or spray solutions. The use of the bounding pH value of 12 allows for conservative results over the entire pH range of 4 to 12.

RAI #27

In Section 6.2.6, the TR discusses verification of the chemical model aluminum dissolution rates. Verification was performed by comparing the average amount of hydrogen generated per minute from the chemical model to the amount obtained with the computer code GENNY for the first three hours after a LOCA. Was the data used to develop the computer code GENNY independent from the data that was used to develop Equation 6-2? If the data is independent, how would inclusion of this data affect the Equation 6-2 coefficients?

RAI #27 Response

The computer code GENNY used data from the Oak Ridge tests and WCAP 7153A and this data was also used in the development of Equation 6-2. Thus, the GENNY database has already been used for Equation 6.2.

RAI #28

Discussion of precipitate formation on Page 78 states that measurable quantities of precipitates were formed in 25 experiments and the volume of precipitate formed for these cases is shown in Figure 5.2-16. This figure identifies the volume of precipitate observed for 14 run/reaction vessel designations. Later in the discussion, the TR indicates that Table 5.2-4 lists the experiments (13 of 60 experiments) where measurable precipitation occurred. Some of the run/reactor identities in Figure 5.2-16 (e.g., P1, P8, Q1) do not match with the identities in Table 5.2-4 (e.g., K2, K4, N2). Please clarify the discrepancy in the

number of experiments with measurable precipitation and test run identifications between Table 5.2-4 and Figure 5.2-16. For all experiments with measurable precipitate, please provide a table showing:

- (a) the run/reactor identification,
- (b) material(s) and test conditions (e.g., pH, temp), and
- (c) the amount of precipitate.

RAI #28 Response

The precipitation runs have been reviewed and the following clarifications are offered.

The discussion refers to 25 experiments in which precipitates formed which is a larger number than in Figure 5.2-16 or Table 5.2-4. The 25 value included runs that were rejected for experimental difficulties. The correct value is 17.

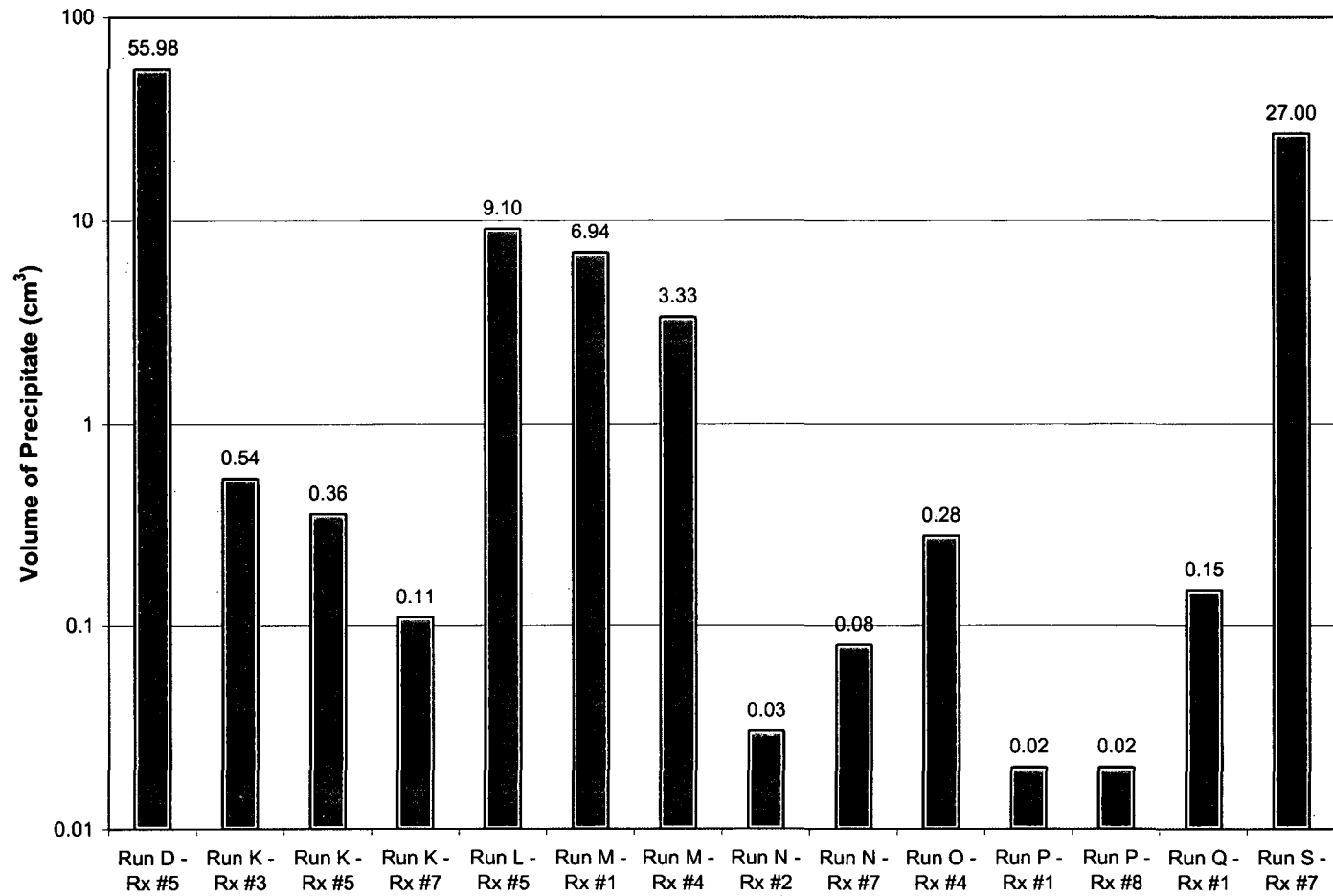
A corrected Figure 5.2-16 is shown below. The original figure included Run M7, a bad run, which has been eliminated. Run N2 was mislabeled as N5, which has also been corrected. The original figure also included only precipitates that formed by cooling from 265 °F. Four runs have been added (D5, P1, P8, and Q1) where precipitates formed upon cooling from 190 °F, even though these runs were not included in the precipitation test matrix. This figure does not include the 3 precipitates that formed by mixing different solutions, since different volumes of solution were involved than for the cooling tests.

A corrected Table 5.2-4 is also shown below. Run M7 was replaced with N7 since M7 was determined to be a flawed run. Also, entries have been added for precipitates that formed from solutions not in the precipitation test matrix. Three columns have been added to clarify the test conditions.

Corrected Table 5.2-4: Experiments with Precipitates

PPT Run	Run/Reactor	Dissolution Run (Soln A)	Material Producing Solution A	pH Solution A	Temperature Solution A	Soln B	Mass of PPT originally in cone	PPT Total Volume settling cone	PPT density	Method of Precipitation
					°F		(g)	(cm ³)	(g/cm ³)	
1	K7	1	Al	4	265	-	0.0016	0.11	0.015	Precipitation from cooling
2	N7	3	Al	8	265	-	Not measured	0.08	Not measured	Precipitation from cooling
3	S7	5	Al	12	265	-	0.6154	27	0.023	Precipitation from cooling,
12	M4	23	Other Fiberglass	12	265	-	0.0103	3.33	0.003	Precipitation from cooling
13	K5	25	Concrete	4	265	-	0.0034	0.36	0.009	Precipitation from cooling,
14	L5	27	Concrete	8	265	-	0.0375	9.1	0.004	Precipitation from cooling
16	K3	31	Mineral Wool	4	265	-	-0.0008	0.54	--	Precipitation from cooling
22	O4	43	FiberFax	4	265	-	0.0028	0.28	0.010	Precipitation from cooling
24	M1	47	FiberFax	12	265	-	0.0427	9.94	0.004	Precipitation from cooling
30	N2	59	Galvanized Steel	12	265	-	0.0045	0.03	0.151	Precipitation from cooling, Galvanized, pH 12
35	K2	7	CalSil	4	265	TSP pH 8	n/a	n/a	n/a	PPT with Phosphate
38	K5	25	Concrete	4	265	TSP pH 8	n/a	n/a	n/a	PPT with Phosphate
60	M4	23	Fiberglass	12	265	E3 (pH 4, CalSil, 190F)	n/a	n/a	n/a	Mixing of solutions from different dissolution runs
Precipitates that Formed but not in Precipitation Test Matrix										
n/a	D5	6	Al	12	190		not measured	55.98	Not measured	Precipitation from cooling
n/a	P1	50	Carbon Steel	4	190	-	not measured	0.02	Not measured	Precipitation from cooling
n/a	P8	12	CalSil	12	190	-	not measured	0.02	Not measured	Precipitation from cooling
n/a	Q1	26	Concrete	4	190	-	not measured	0.15	Not measured	Precipitation from cooling

Revised Figure 5.2-16: Volume of Precipitate Observed in the Settling Cones



RAI #29

Table 5.2-5 provides elemental analysis of the precipitates formed during testing. Based on the elemental values shown in this table, a "best guess" precipitate is identified.

- (a) If the compositions reported in this table are average values, please indicate the number of areas analyzed to obtain an average and the range in the percentages for each element when an average value was reported.
- (b) Was the precipitate rinsed with deionized water prior to analysis?
- (c) Was the energy dispersive spectroscopy system used to obtain these results capable of detecting boron? For example, would boron be detected by this analysis if it was adsorbed onto the surface of an aluminum oxyhydroxide precipitate?
- (d) what is the source of the copper reported for most of the precipitates?
- (e) Since identification of precipitates provides the basis for chemical surrogates that may be used in strainer head loss testing, explain why supplemental quantitative chemical analysis is not needed to establish the precipitate identity with greater accuracy?

RAI #29 Response

- (a) Typically only one area scan approximately 20 microns in size was performed. Due to the small particulate size, a 20 micron scan was considered sufficient.
- (b) The precipitate was rinsed with deionized water.
- (c) EDS is only sensitive to boron in large amounts. Boron can be detected in boron carbide by EDS (54 wt%), but cannot be detected in thin boric acid deposits (B<17 wt%).
- (d) Copper tape was used to hold down the filter paper.
- (e) The focus of the effort was to identify the general chemical make up of the prototypical precipitates and to investigate the physical attributes of the precipitates that could affect sump screen performance (i.e., settling rate and qualitative filtration behavior). This information was used to develop surrogate materials that are chemically similar and have essentially the same filtration characteristics. For example, testing demonstrated that a key class of precipitates was composed of compounds containing a metal (sodium or calcium), aluminum and silicon (presumably as silicate). Thus, a surrogate was prepared by combining aluminum (as aluminum nitrate), sodium and silicon (as sodium silicate). The surrogate material exhibits the same filtration properties as the precipitate generated in the bench tests. Although it is assumed that both materials are sodium aluminum silicate ($\text{NaAlSi}_3\text{O}_8$), the filtration behavior is the attribute of interest.

RAI #30

Within Section 5.4, Precipitate Filterability Tests, the terms filter cake coefficients, filtration constants, filter solids constants, and filterability coefficient are used. Please define these terms and indicate if they refer to the same parameter.

RAI #30 Response

Section 5.4 of the WCAP has been revised and will be sent as part of the response to the RAIs. All references to filter solids constant, filtration constants, and filterability coefficients have been replaced in the text by the overall filter cake coefficient (K_f) and the filter cake coefficient for a specific precipitate (K_{fx}). The terms are defined as follows:

K_f = overall filter cake coefficient ($\text{gpm ft}^{-2} \text{psi}^{-1} \text{cP}^{-1}$)

K_{fx} = filter cake coefficient for a specific precipitate or solid x ($\text{gpm lb}_m \text{cP ft}^{-4} \text{psi}^{-1}$)

RAI #31

The filterability tests provided information about the hydraulic characteristic of the precipitates. It is stated that the lower filtration constants can be used as an initial guess for calculating pressure drops. Please describe the formation of the filter cake and the material composition of the cake. Evaluate the relevance between the filter cake and debris bed under plant LOCA conditions, and demonstrate why Equation 5-1 can even be used as an initial guess without the real debris bed formation sequence and material compositions.

RAI #31 Response

The data obtained regarding composition of the precipitates can be found in Table 5.2-4 (Experiments with Measurable Amounts of Precipitate) and 5.2-5 (SEM Analysis of the Precipitates). A debris bed was not generated for the experiments due to the highly variable nature of the debris. Instead a commercial fiber filter was used. With respect to Equation 5-1, it was assumed that the bed was impervious to precipitate.

On the other hand, this does not eliminate the possibility of open channels since these also can hold precipitate. Also, the pressure drop data obtained are not intended to be used for calculating actual pressure drop across the plant scale filtration units. Rather, the purpose of collecting this information was to obtain an indication of the filterability of the precipitates. This approach gives a bounding worst case evaluation since there are assumed to be no channels formed. Any channels will tend to decrease pressure drop over the bed.

RAI #32

Equation 5-1 is used as the basis to correlate the test data collected from the filterability tests. According to Equation 5-1, the pressure drop across the debris bed appears to be a function of flow velocity, specific dry solids loading (lb/ft^2), water viscosity and total screen/filter flow area. Assuming that we have two filter cakes with different flow area, but the same water viscosity, flow velocity, and specific dry solids loading, the pressure drop across the screen decreases with larger flow area (using this equation). The NRC staff would expect the pressure drop under these conditions to remain constant. Please explain the origin of the equation and justify the correctness of the correlation.

RAI #32 Response

As mentioned in our response to RAI #30, the units of F the volumetric flow rate are GPM not GPM/ft^2 as was indicated in the original version of the equation.

RAI #33

Equation 5-2 through Equation 5-5 were developed to account for a debris bed with different layers of material compositions. Please explain how these equations could be applied to plant conditions following a postulated LOCA where the debris bed material compositions, particulate/fiber ratios, and chemical precipitate specific mass are not measured or the bed morphology is not known.

RAI #33 Response

The response to RAI #31 indicates that this equation can be used if it is assumed that debris has made the filter impervious to precipitate. On this basis, the equation cannot be applied to a plant screen. This is a worst case approach to estimating the pressure drop.

As stated in RAI #31, the pressure drop data obtained in these experiments was not intended to be used for calculating pressure drop across the plant scale filtration units. Rather, the reason for collecting the pressure drop data was to obtain an indication of filterability.

RAI #34

In Section 5.4.4, discussion of filterability test results, the TR states, "For PPT runs 1, 14, and 16, the head loss with debris laden filters is comparable to or less than the clean filter head loss. This anomaly may be attributed to either some bypass of the filter or slight errors in the pressure measurements that could cause a negative number when the difference of two small numbers is determined." Please discuss how the filter could have been bypassed. If filter bypass potentially occurred during these tests, discuss the implications on the reliability of all the test results including justification why all the filterability test results should not be repeated using a test that ensures filter bypass will not occur.

RAI #34 Response

The filtration tests were performed using filter discs which fit into a housing that screwed together to provide a seal. The referenced sentence in the WCAP recognizes that bypass could theoretically occur in the event that the filter was not properly seated within the housing. In such an event, a "negative" head loss might be measured. In fact, this condition would be more likely to result in a zero or lower-than-expected head loss measurement. As noted, the other potential for apparently negative head loss values is the subtraction of two small delta P values, each with their associated uncertainties.

Although there was some unlimited potential for bypass to occur, there were no indications that bypass did occur in any of the filtration runs. The intent of the filtration tests was to obtain a qualitative indication of the relative filterability of the precipitates tested. In all cases, the precipitates tested created high head loss at low concentration, consistent with the results of the ICET and other test programs. Thus, there is no indication that filter bypass occurred to an extent that would call the results into question.

RAI #35

Filterability tests were conducted using a 1 micron glass fiber filter. Previous evaluation of chemical product particle sizes indicate simulated ICET 1 chemical products range in size depending on agglomeration of nanoparticles. For example, Los Alamos National Lab (LANL) identified particle size aggregates of approximately 0.5 microns. In addition, particle sizing (after ultrasonic deflocculation) of ICET 1 simulated chemical product at Argonne National Laboratory showed approximately one third of the particles were less than 1 micron. Discuss how the potential range of precipitate sizes could affect the filterability test results.

RAI #35 Response

As discussed previously, filtration testing was performed to provide a measure of the suitability of surrogate precipitates and to provide a qualitative measure of filterability. The testing was not intended to generate data to be used for any other purpose. On this basis, use of filters of a consistent size and porosity for all filtration tests is logical.

It should be noted that the precipitates tested blinded the glass fiber filters at relatively low concentration, consistent with results reported from the ICET program. It is reasonable to expect that the glass fiber filters used in the test have a lower effective porosity than a fiber bed on a sump screen. Thus, the filtration data may reasonably be used as a qualitative measure of whether the precipitates could increase head loss on a strainer.

RAI #36

Table C-1 provides a summary of filtration results. The method of precipitate formation (e.g., PPT on cooling, concrete, pH 4) shown for the various precipitation test runs in Table C-1 does not match the descriptions previously provided in Tables 5.2-4 and Table 5.4-1. Please clarify.

RAI #36 Response

The column "Method of Precipitate Formation" in Table C-1 should be revised to be consistent with Tables 5.2-4 and 5.4-1. The adjusted column is provided below.

PPT Run	<i>Original Table C-1</i>	<i>Revised Table C-1</i>
	Method of Precipitate Formation	Method of Precipitate Formation
1	PPT on cooling, Concrete, pH 4	PPT on cooling, Aluminum, pH 4
2	PPT on cooling, Concrete, pH 8	PPT on cooling, Aluminum, pH 8
3	PPT on cooling, Mineral Wool, pH 4	PPT on cooling, Aluminum, pH 12
12	PPT on cooling, FiberFax, pH 4	PPT on cooling, Other Fiberglass, pH 12
13	PPT on cooling, FiberFax, pH 12	PPT on cooling, Concrete, pH 4
14	PPT on cooling, FiberFax, pH 12	PPT on cooling, Concrete, pH 8
16	PPT on cooling, FiberFax, pH 12	PPT on cooling, Mineral Wool, pH 4
22	PPT on cooling, FiberFax, pH 12	PPT on cooling, FiberFax, pH 4
24a	PPT on cooling, Galvanized, pH 12	PPT on cooling, FiberFax, pH 12
24b	PPT of Phosphates, CalSil	PPT on cooling, FiberFax, pH 12
24c	PPT of Phosphates, Concrete	PPT on cooling, FiberFax, pH 12
24d	pH 12 265 Fiberglass with pH 4 CalSil	PPT on cooling, FiberFax, pH 12
30	PPT on cooling, Concrete, pH 4	PPT on cooling, Galvanized, pH 12
35	PPT on cooling, Concrete, pH 8	PPT of Phosphates, CalSil
38	PPT on cooling, Mineral Wool, pH 4	PPT of Phosphates, Concrete
60	PPT on cooling, FiberFax, pH 4	pH 12 265 Fiberglass with pH 4 CalSil

RAI #37

The mass of precipitate filtered for PPT 16 in Table C-1 is shown as a negative value. In addition, the K_{fx} for PPT 3 in Table C-1 does not match the K_{fx} reported in Table 5.4-1. Please clarify.

RAI #37 Response

In the case of PPT 16, the dP versus flow data indicate that the head loss with debris laden filters is comparable to or less than the clean filter head loss. This anomaly may be attributed to some filter bypass or slight errors in the pressure measurements which could cause a negative number when the difference of two small numbers is determined. Additional input regarding this subject can be found in the response to RAI #34.

In the case of PPT 3, the data shown in Table C-1 represents data taken from run PPT 3a. The original PPT 3 was disregarded and PPT 3a became PPT 3.

The disagreement in the values of K_{fx} for PPT 3 in Tables C-1 and 5.4-1 has been resolved. A value of 0.0008 will be reported in both tables.

RAI #38

Please interpret the meaning of the data provided in Figure C-2.

RAI #38 Response

Reaching equilibrium in the initial part of this test appears to have taken more time than expected. However, once this condition was attained the pressure drop versus flow data obtained was suitable for further analysis. That is, a positive slope was obtained on a pressure drop (dependent variable) versus flow (independent variable) plot. In turn, this resulted in positive values for K_{fx} and K_f .

RAI #39

The chemical model spreadsheet does not provide an input value for zinc although it shows zinc released in subsequent Excel sheets. Although testing has shown zinc may not be an important contributor to chemical effects, discuss why there is not a link between the input sheet and the "zinc released submerged" and "zinc released unsubmerged" sheets for consistency?

RAI #39 Response

Because zinc was determined in Section 6.2.2 of WCAP-16530 to be an insignificant contributor to the potential post-accident chemical effects, the input was not included in the "Materials Input" worksheet. The latest version of the chemical model spreadsheet does not include the zinc release evaluation in light of this determination.

RAI #40

The WCAP determines the amount of sodium aluminum silicate relative to aluminum oxyhydroxide based on previous thermodynamic based chemical speciation work (NUREG-CR-6873). This thermodynamic work, however, did not consider reaction kinetics or potential influences of one material on another. Discuss how these could affect the relative amounts of these precipitates that are formed.

RAI #40 Response

The chemical model assumes all aluminum precipitates as either a silicate or an oxyhydroxide. As noted, aluminum is assumed to precipitate preferentially as the silicate based solely on thermodynamic considerations. On a mass basis, this results in a greater quantity of precipitate, and is thus considered

conservative. The filtration properties of sodium aluminum silicate and aluminum oxyhydroxide are qualitatively identical.

RAI #41

In Section 7.1, the WCAP states that after generation in the particle generator unit, the chemical products may be treated as another class of inert debris for strainer testing purposes. Please clarify this statement. Is this statement intended to signify that product generated using the procedures provided in the WCAP can be considered as surrogate chemical product or does it indicate that these products will not interact with any other materials/environments in strainer vendor testing? If this statement should be interpreted as the latter, provide the basis for this conclusion, considering that these particles may provide an environment for entrapment of additional materials through co-precipitation and flocculation.

RAI #41 Response

The statement was intended to indicate that the precipitates would not be chemically interactive with other debris. It is recognized that important physical interactions may occur, for example if precipitates caused agglomeration of suspended debris such as small fibers. The significance of such interactions would be obvious in strainer testing.

RAI #42

In Section 7.1 concerning the particulate generator, the WCAP states that the filtration and settling behavior of the key precipitates are influenced by the amorphous and hydration properties of the materials. The WCAP further states that if crystalline, non-hydrated, or other manufactured solid starting materials are used for screen testing, it is suggested that testing be performed to demonstrate their acceptability. How were the chemical products generated using the directions shown in Section 7.3.2 verified to be amorphous?

RAI #42 Response

The primary basis is that the filtration and settling behavior of the surrogate materials are indicative of hydrated/amorphous material. Additionally, no crystalline structure was observed in high magnification SEM analysis. Finally, subsequent testing with commercially available manufactured crystalline sodium aluminum silicate showed that this material settled rapidly and was far more easily filtered than the material prepared in accordance with the directions in the WCAP.

RAI #43

TR guidance for chemical precipitate formation is provided in Section 7.3.2. The directions for forming aluminum oxyhydroxide call for the addition of aluminum nitrate to potable water followed by sodium hydroxide addition. Calcium phosphate and sodium aluminum silicate precipitates are also generated using potable water. Considering that LANL work (presented at the June 2006 ACRS Thermal-Hydraulic Subcommittee Meeting) suggested that the ICET 1 precipitate remained amorphous as a result of boron inhibiting crystallization,

(a) Are the chemical precipitates generated using the WCAP directions representative (e.g., similar response to pH and temperature changes, produce similar pressure drop across a fiber bed) of the amorphous chemical products observed in ICET?

- (b) Is the aluminum oxyhydroxide generated using the WCAP procedure a crystalline or amorphous product?
- (c) Would a different chemical precipitate structure be formed if sodium hydroxide were first added to borated water to create an alkaline solution with subsequent aluminum nitrate addition?
- (d) discuss why precipitation from homogeneous solutions will form precipitates that are representative of those formed as a result of leaching and bulk chemical addition in the presence of non-dissolved containment materials (i.e., insulation)

RAI #43 Response

- a) Yes, the characteristics of the precipitates prepared in accordance with the directions in the WCAP are comparable to the precipitates evaluated in the ICET program.
- b) As noted above, the settling and filtration characteristics of the aluminum oxyhydroxide generated in accordance with the directions in the WCAP are indicative of a hydrated/amorphous material.
- c) It is possible that the presence of other dissolved species such as boron could affect the chemical form of the precipitates. However, the settling and filtration characteristics would not be measurably affected by minor changes in the chemical composition due to incorporation of ionic species.
- d) Generation of precipitates in a well-mixed system with all reactants at stoichiometric concentration is conservative with respect to formation *in situ*. In a non-homogeneous system, the rate and degree of precipitation would be controlled by the local concentration of reactants. Precipitation would slow as the concentration of the limiting reactant was reduced. For example, precipitation of calcium phosphate would be controlled by the local concentration of calcium and phosphate. In the event calcium dissolution proceeded slowly, precipitate formation would be slow. In the well-mixed, stoichiometric concentration case, precipitation goes to completion essentially instantaneously.

RAI #44

Within the particulate generator qualification testing discussion, the TR states the settling and filtration characteristics of the particle generator products were consistent with those in the bench scale testing. Settled volume is provided in Tables 7.5-1 and 7.5-2 but filtration results are not shown. Please provide the filterability test results for the particulate generator products.

RAI #44 Response

In addition to the settling test results presented in the WCAP, bench scale filterability tests were also conducted. These tests used the same procedures described in the WCAP.

A total of 10 runs were made. Two of the runs produced suitable pressure drop (dependent variable) versus flow (independent variable) plots. However, no weight gain was obtained for these runs. As a result, values for the filter coefficients can not be calculated. Since it would appear that the filter functioned over most of the test, these runs have been incorporated into Table C-1 as runs PG-9 and PG-10. Of the 8 remaining runs, two test conditions were duplicated. One set was duplicated 3 times (a total of 4 runs) while the other test was duplicated once (a total of 2 runs). A summary of these test results is presented in the table below.

Particulate Generator Test Results

Run Number	Sample Preparation Method	K_{fx} (gpm lb _m cP ft ⁻⁴ psi ⁻¹)	K_f (gpm ft ⁻² cP ⁻¹ psi ⁻¹)
PG-1*	2.2 g/l Aluminium Oxide Hydroxide in Tap Water	0.005	0.07
PG-2*	Same as Above	0.0019	0.18
PG-3*	Same as Above	0.0022	0.42
PG-4*	Same as Above	0.0031	1.47
PG-5**	2.2 g/l Aluminium Oxide Hydroxide in 4400 ppm Boron	0.0001	0.04
PG-6**	Same as above	0.0001	0.04
PG-7	1 g/l Calcium Phosphate in 4400 ppm Boron	0.0085	5.34
PG-8	Same Preparation as PG-1 but Sample Volume Doubled to 2 ml	0.0004	0.03
PG-9	1 g/l Calcium Phosphate in 4400 ppm Boron – Sample Volume Increased to 10 ml	Not available	Not available
PG-10	1 g/l Calcium Phosphate in Tap Water – Sample Volume to 10 ml	Not Available	Not Available

*Set of 4 runs

** Set of 2 runs

RAI #45

Figures 7.6-1 and 7.6-2 show the settling rates for aluminum oxyhydroxide and calcium phosphate, respectively, as a function of mix tank concentration. The y-axis in these figures show the precipitate settled volume. For the plots provided, clarify if the y-axis values represent the amount of volume containing precipitate. In other words, if there were 2 ml of clear solution above a cloudy solution containing precipitate, would the settled volume shown be 8 ml?

RAI #45 Response

The settled volume in Figures 7.6-1 and 7.6-2 is shown on the y-axis as the volume of the solution which contains observable precipitate. A 10 mL solution for which the bottom 8 mL are “cloudy” and the top 2 mL are clear would have a settled volume of 8 mL. This method is consistent with that used to record the settled volume of the precipitate reported in Table 5.3-1.

RAI #46

Section 7.6 discusses the effects of concentration of generated precipitate on its settling characteristics. Bench scale testing was performed to determine the settling characteristics of generated precipitate as a function of mix tank concentration. After 60 minutes, the change in settled volume between the allowable aluminum oxyhydroxide concentrations appears to be much greater than the change in settled volume between the allowable calcium phosphate concentrations. Discuss the rationale used to determine the mix tank concentrations that should not be exceeded for aluminum oxyhydroxide and calcium phosphate precipitates.

RAI #46 Response

The maximum mix tank concentrations were selected in consideration of the fact that precipitates would be added directly to a flowing test system and would transit through in minutes. The values were selected

to balance practicality (primarily relative size of the surrogate mixing tank with respect to the test flume volume) and the need to use prototypical precipitates. The difference in the settled volume for aluminum oxyhydroxide (3.0 milliliters) and calcium phosphate (2.1 milliliters) in the un-concentrated case versus the concentrated case is not considered large.

RAI #47

Table 7.8-1 provides the minimum physical characteristics of surrogate precipitates. For precipitate settling, the table shows a criterion for a one-hour settled volume greater than 4.0 ml for the three precipitates. For strainer performance testing, it is more conservative to have precipitates remain in suspension. Therefore, discuss the rationale for the settled volume requirement greater than 4.0 ml. In addition, discuss how consistency in surrogate settling data interpretation and settling test technique are maintained between these tests and those that may be performed by strainer vendors.

RAI #47 Response

It is recognized that it is more conservative for precipitates to remain in suspension during strainer testing, and the one-hour settling volume test is a means to ensure that surrogate precipitates indeed remain in suspension for a prototypical duration. The one-hour settling volume criterion was established to provide a consistent basis to evaluate precipitates prepared by individual screen vendors with precipitates prepared during the test program reported in the WCAP. In turn, the characteristics of the surrogates prepared in the PWROG test program were compared with the characteristics of precipitates generated during bench testing of containment materials/buffering agents. This approach provides assurance that the surrogate materials prepared by the vendors are indeed prototypical.

RAI #48

Section 7.8 discusses settling rate and filtration characteristics that should be met if alternate (other than recommended in the WCAP) precipitate materials are used by strainer vendors. The WCAP states that in such cases, it may be necessary to pre-soak the material in water for several hours/days to ensure the proper degree of hydration is obtained. Thermogravimetric Analysis performed by LANL (presented at the June 2006 ACRS Thermal-Hydraulic Subcommittee Meeting) indicated that chemical surrogate generated with aluminum in sodium hydroxide and boric acid solutions are highly hydrated.

(a) Discuss how it is determined that the proper degree of hydration is obtained for the precipitates formed per Section 7.3.2 in the WCAP.

(b) In addition, it appears the formulas for determining plant specific chemical products do not include waters of hydration. Discuss how waters of hydration are accounted for in the chemical model output that would be used to inform subsequent sump strainer performance testing.

RAI #48 Response

a) As discussed in the response to item 42 above, the filtration and settling characteristics of the surrogate precipitates were compared to the characteristics of precipitates generated in bench testing of containment materials/buffers. These data were used to conclude that the degree of hydration was comparable.

b) The degree of hydration was not determined for either the surrogate materials or the precipitates generated in bench testing. Rather, the settling and filtration characteristics of the precipitates were used to infer that the materials were hydrated to an equal degree. The mass of the waters of hydration was not included in the mass of precipitates calculated in the chemical model. Consistent with this, the recipes for

the surrogate materials only include the mass of the metal (calcium or aluminum) and anion (phosphate, silicate or hydroxide).

RAI #49

Bench test dissolution results (page 134) indicate that for most tests with Durablanket in pH 8 solution, there is little change to the solution pH during the test. For test Runs Q4-1, Q4-2, and Q4-3, however, the pH drops significantly during the test duration. Provide any insight (e.g., sample variability, testing anomaly) you may have to explain this data.

RAI #49 Response

This was a transcription error. The Q4 runs actually started out at pH 4.1, so the pH increased during the run as would be expected. Run Q4 was a duplicate run, and the erroneous pH values were not used in the model development.

RAI #50

It is the staff's understanding that there have been some changes to the WCAP-16530-NP Chemical Model Spreadsheet. Please provide an updated copy of the chemical model spreadsheet and discuss the impact of any changes that have been made to the spreadsheet.

RAI #50 Response

The first error requiring a change to the spreadsheet was communicated to the NRC via Owners' Group letter, WOG-06-107, in March 2006. This error was discovered in the saturation constant coefficients presented in Table 6.2-3 of WCAP-16530 used to determine the release rate equations for the aluminum and silicon released from mineral wool and the silicon released from Interam.

Subsequent changes to the spreadsheet include:

- a) An error was discovered in the Si Release column of the "Results Table" worksheet; the silicon release from silica powder material, i.e., Microtherm and Min-K, was not included in the sum. An additional error was found in Cell F15 of the "Materials Conversion" worksheet. This cell incorrectly referenced the total volume of silica powder insulation as opposed to the total mass.
- b) In three of the worksheets which calculate the calcium releases for concrete (Conc), fiberglass or E-glass (EG) and mineral wool (MW), "Ca from Conc," "Ca from EG," and "Ca from MW," the incorrect row is referenced in the "Time Temp pH" worksheet Column G containing the flag to credit sump mixing. One row above that intended is referenced, so in the time period that sump mixing is credited, the calculated dissolution rates for these materials will still be dependent upon the calcium release from that material alone. The calculated dissolution rate based on the total calcium release from all materials will not be implemented until the subsequent time period.

An updated copy of the spreadsheet has been provided with the submittal of these RAI responses on the enclosed CD.

Attachment 2

REVISION of SECTION 5.4

5.4 PRECIPITATE FILTERABILITY TESTS

5.4.1 Summary

Precipitate filterability tests were carried out at the Westinghouse Science and Technology Department to determine the overall filter cake coefficients (K_f) for the various precipitates produced in the chemical effects bench testing discussed in Section 5.2. The results of these tests indicated that chemically induced precipitates produced solids with single component filter cake coefficients (K_{fx}) (average = 0.0034+/-0.0022) about half that of the Si and Al precipitates (0.0032+/-0.00202) formed on cooling. This indication comes from a relatively limited dataset and so needs to be used with care. However, the lower values could be used as an initial guess for calculating maximum pressure drops.

5.4.2 Filtration Model

The data obtained from this experiment was modelled using the following equation:

$$F = (K_{fx} / m_x) * A * dP / n \quad (\text{Equation 5-1})$$

Where:

F = total flow rate (gpm)

K_{fx} = filter cake coefficient for a specific precipitate or solid x (gpm lb_m cP ft⁻⁴ psi⁻¹)

dP = measured pressure drop across filter with solids (psi or lb_f in⁻²)

n = viscosity of the liquid in the slurry (assumed to be water) (cP)

m_x = specific dry (1 hour @ 110°C) solids x loading (lb_m ft⁻²)

A = flow area (ft²)

This model makes the assumption that the filter cakes are relatively thin and incompressible. This assumption was made since the applied pressure drops will be very small (on the order of 1 to 6 psi). Note that this assumption was supported by the data in that all the pressure versus flow plots obtained experimentally were reasonably linear in the low delta P regions.

To apply this test data to calculations for screen pressure drops, the following data is required:

1. The method of bed formation, i.e., whether the bed is formed from a mix of solids or formed by layering of various solids
2. Specific dry (1 hour @ 110°C) weight of each solid (lb_m ft⁻²)
3. Either the temperature to determine the viscosity if water is assumed or the measured liquid (not slurry) viscosity
4. The K_{fs} of the screen (gpm ft⁻² psi⁻¹ cP⁻¹) determined with the viscosity at the temperature of interest

5. Total flow rate (gpm) and area (ft²)

If the bed is formed in layers, then the overall K_f can be determined analogous to the method used to determine an overall heat transfer coefficient. That is:

$$1/K_f = 1/K_{fs} + \sum m_x/K_{fx} \quad (\text{Equation 5-2})$$

Where:

K_{fs} = the screen coefficient (gpm ft⁻² psi⁻¹ cP⁻¹)

m_x = specific mass of each solid (lb ft⁻²)

K_{fx} = filter cake coefficient for a specific for a specific precipitate x (gpm lb_m cP ft⁻⁴ psi⁻¹)

A simple mass-weighted approach may be used as a theoretical means to determine the effective K_f for a mix of solids as opposed to a single solid.

$$K_{fz} = \sum K_{fx} / m_x \quad (\text{Equation 5-3})$$

where K_{fz} is the effective K_f for the mixed solids bed.

This K_{fz} can then be used along with the screen K_{fs} in the equation below to determine the overall K_f .

$$1/K_f = 1/K_{fs} + 1/K_{fz} \quad (\text{Equation 5-4})$$

Finally, K_f can then be used to determine the pressure drop using the equation:

$$dP = F / (K_f * A / n) \quad (\text{Equation 5-5})$$

5.4.3 Test Procedure

After forming precipitates in the first portion of testing described in Section 5.2, the precipitates were then tested in a filter apparatus to determine their overall filter cake coefficient using the procedure given below and the apparatus shown in Figure 1 below. The solution containing the precipitate was pumped through a filter at different flow rates in order to record the pressure drop at each flow rate. The filtration experiments were done at room temperature (between 70°F and 78°F).

Equipment List

- 4-Channel Peristaltic Pump, Pump Head Cole Parmer EW-07519-10 with cartridges Cole-Parmer EW-07519-85 and pump tubing EW-06508-14
- Pressure sensor 1- Omega PX303-0 0A10V 0-50 psia
- Pressure sensor 1- Omega PX303-050A5V 0-50 psia
- Flow sensor- McMillan Co 104 Flo-Sen S/N 1011 3
- Tubing outside pump- Cole-Parmer L/S 14 Tubing, C-96410-14
- Filter Holder-25 mm Filter Holder VWR 28144-164

- Filter – 25 mm glass fibre filter, 1-micron, 28150-134

Preparation

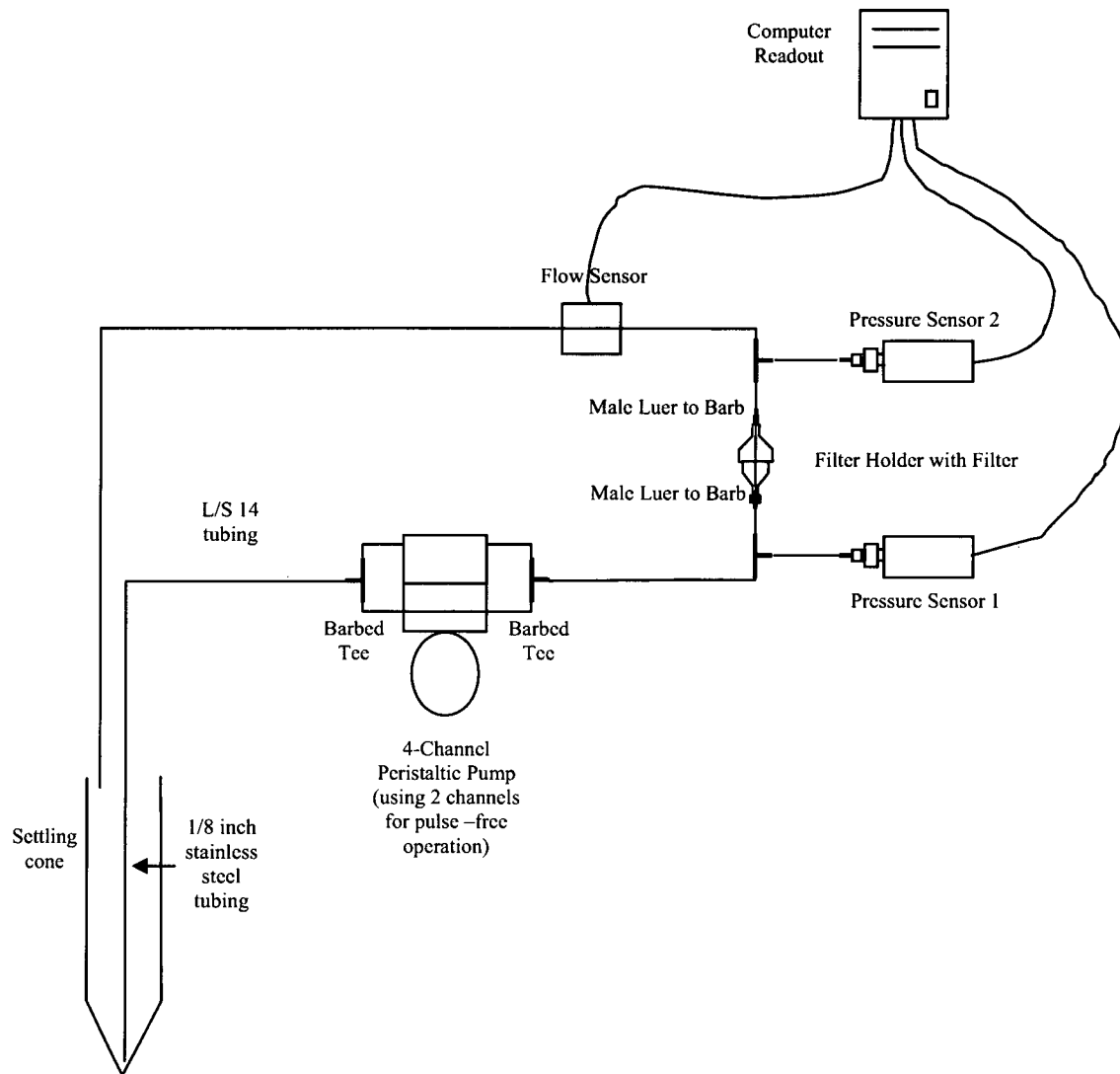
- Calibrate the program in order to obtain pump flow rates. Three flow rates are used in order to determine the change in pressure drop with flow rate.
- Select a 1-micron glass fibre filter and weigh it to the nearest 0.0001 g.
- Place the fibre filter in the holder.
- Measure 75 ml of 4400 ppm boron solution into settling cone.
- Place the dip tube and the return line in the settling cone.

Filtration

- Turn on the pump and set flow rate to the highest flow rate in order to load the filter at the beginning of the test.
- Allow sufficient time for the flow to stabilize through the filter (5 minutes). Then thoroughly shake the solution containing precipitate and add approximately 10 ml to the settling cone.
- Record pressure drop across filter with time.
- After the total solution volume has passed through the filter about four times, decrease the pump flow rate.
- Record pressure drop with time.
- After the total solution volume has passed through the filter about four times, again decrease the pump flow rate.
- Record the pressure drop with time, until approximately another 4 solution volumes have passed through the filter.

End of Experiment Tasks

- Rinse the filter with 10 ml of de-ionized water.
- Dry the filter at 110°C +/- 10°C for 1 hour.
- Weigh the filter.
- Place filter in a labelled container for later SEM analysis.
- Clean loop before next test with a flow of de-ionized water.

Figure 1 - Filter Test Equipment Schematic

The experimental data obtained were:

f = flow rate (ml/min) as a function of dP (psi)

n = water viscosity (cP) from the temperature (°F)

m = dry (110°C @ 1 hour) solids (gm)

$A = 3.8 \text{ cm}^2$ measured exposed filter area

A representative figure (Figure 2 below) containing the dP versus flow rate data recorded as a function of time is presented below. Similar data is available for all of the runs conducted in order to gauge the filterability of the precipitate.

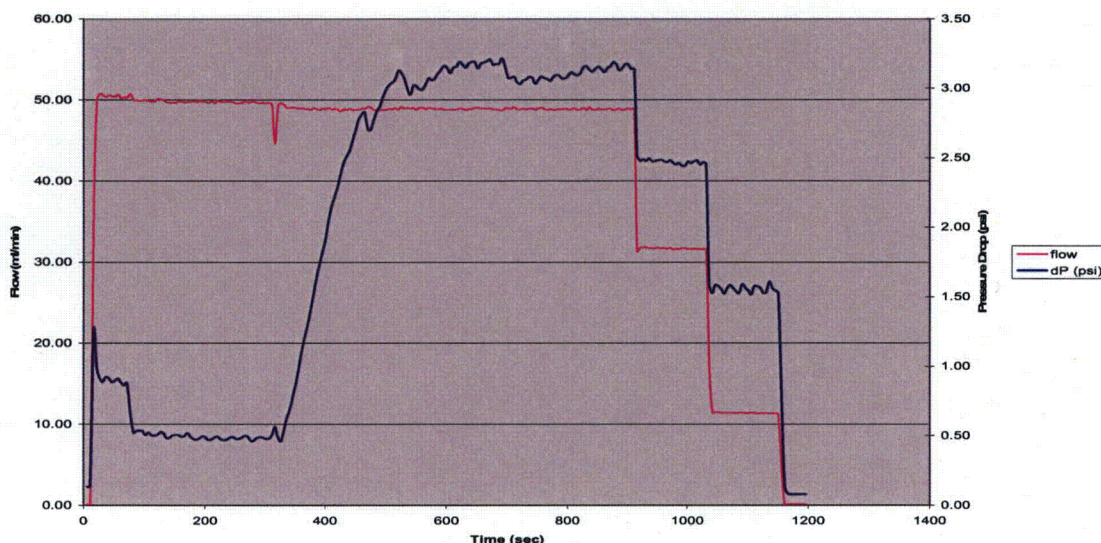


Figure 2 - dP and Flow Rate as a Function of Time for PPT 24D

Graphs of the dP versus flow rate (ml/min) are shown in Appendix C. Each set of data was analyzed in the linear portion using least squared regression analysis to obtain the slope of the curve (z in psi-min/ml). Note that some curves bent over, i.e., the flow increased with little or no increase in pressure drop. The higher flow data from these tests was not used since the upper flow data was likely taken before the solids had finished depositing on the filter. Also, some near-zero point data was not used since at very low delta P values, there were instabilities in some of the delta P measurements. The range of data that was used from each test is indicated on the data plots given in Appendix C. This slope was then combined with the water viscosity, solids weight and effective filter area to determine the overall (filter + cake) K_f using the equation:

$$K_f = n / A^2 / z / [3785 \text{ ml/gal}] \quad (\text{Equation 5-6})$$

The K_{fs} (filter cake coefficient for a specific precipitate) was obtained from the slope (z) of the dP versus flow measurement for the filter (Figure C-1) using the equation:

$$K_{fs} = n / A^2 / z / [3785 \text{ ml/gal}] \quad (\text{Equation 5-7})$$

Note that by using the slope, it was assumed that the pressure versus flow data passed through the point 0,0. The K_{fx} (filter cake coefficient for a specific precipitate ($\text{gpm lb}_m \text{ cP ft}^{-4} \text{ psi}^{-1}$)) was then obtained by substituting Equation 5-7 into Equation 5-2 and solving the resulting equation for K_{fx} :

$$m / A / K_{fx} / [454 \text{ gm/lb}] = 1/K_f - 1/K_{fs} \quad (\text{Equation 5-8})$$

Note that the K_{fs} was corrected to the viscosity at the temperature at which each filtration test was run.

5.4.4 Results

The results from these tests are summarized in Table 1 below. The dP versus flow data is presented for each run in Appendix C. These results indicate that the K_{fx} for the various precipitates range from 0.0001 to 0.0066 after discounting results from those PPT tests that had too little precipitate to result in a discernible dP measurement: PPT runs 1, 13, 14, 16, 22 and 30.

For PPT runs 1, 14, and 16, the dP vs. flow data indicate that the head loss with debris laden filters is comparable to or less than the clean filter head loss. This anomaly may be attributed to either some bypass of the filter or slight errors in the pressure measurements which could cause a negative number when the difference of two small numbers is determined.

The remaining PPT runs are listed below.

Table 1: Precipitate Filter Coefficients

PPT Run	Precipitation Formation Method	Individual Filter Cake Coefficients (K_{fx})	Overall Filter Cake Coefficients (K_f)
2	PPT on cooling, Al pH 8	0.0033	0.15
3	PPT on cooling, Al pH 12	0.0008	0.93
12	PPT on cooling, Other Fiberglass, pH 12	0.0009	1.15
24a	PPT on cooling, FiberFax, pH 12	0.0066	1.81
24b	PPT on cooling, FiberFax, pH 12	0.0043	1.30
24c	PPT on cooling, FiberFax, pH 12	0.0027	0.88
24d	PPT on cooling, FiberFax, pH 12	0.0039	1.19
35	PPT of Phosphates, CalSil	0.0033	1.93
38	PPT of Phosphates, Powdered Concrete	0.0001	0.05
60	pH 12, 265 Fiberglass (high sulfur), with high calcium from pH 4 CalSil.	0.0017	1.87

This data indicates that:

1. Phosphates cause precipitation by super saturation at temperature and have low individual filter cake constants (K_{fx}) (average = 0.0034 +/- 0.0022). The other precipitate, PPT 60, has a similar value of K_{fx} (0.0017). The large uncertainty of the results is due to the limited number of phosphate precipitation runs for which filtration filter coefficients may be developed.

2. The Si and Al precipitates formed on cooling have relatively high individual cake coefficients (K_{fx}) (0.008 to 0.0066, average = 0.00321 +/- 0.00202).
3. The repeated PPT24 runs had an average K_{fx} of 0.00438 +/- 0.00163 with a range of 0.0027 to 0.0066. This is about the same as the entire set of data (average = 0.00276 +/- 0.00196).

SECTION D



Program Management Office
4350 Northern Pike
Monroeville, Pennsylvania 15146

WCAP-16530-NP, Rev. 0 (Non-Proprietary)
Project No. 694

April 3, 2007

OG-07-129

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Subject: Pressurized Water Reactor Owners Group
Responses to the NRC Second Set of Requests for Additional Information (RAI's)
on WCAP-16530, "Evaluation of Chemical Effects in Containment Sump
Fluids to Support GSI-191"

References:

1. NRC letter from Sean E. Peters of NRR to Gordon Bischoff of PWROG dated October 4, 2006, "Request for Additional Information RE: Westinghouse Owners Group (WOG) Topical Report WCAP-16530-NP, 'Evaluation of Post Accident Chemical Effects in Containment Sump Fluids to Support GSI-191' (TAC NO. MD1119)."
2. WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February 2006.
3. PA-SEE-0275, Revision 1, "Method for Evaluating Post-Accident Chemical Effects in Containment Sump Fluids," June 2006.
4. PWR Owners Group letter, OG-06-387, "Pressurized Water Reactor Owners Group: Responses to the NRC Request for Additional Information (RAI) on WCAP-16530, 'Evaluation of Chemical Effects in Containment Sump Fluids to Support GSI-191'," November 21, 2006.
5. NRC letter from Sean E. Peters of NRR to Gordon Bischoff of PWROG dated March 23, 2007, "Request for Additional Information RE: Pressurized Water Reactor Owners Group Topical Report (TR) WCAP-16530-NP, 'Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191' (TAC NO. MD1119)."

The Nuclear Regulatory Commission (NRC) requested additional information via letter dated October 4, 2006 (Reference 1) to support the review of the Westinghouse topical report, WCAP-16530-NP (Reference 2). The topical report was generated to support the Pressurized Water Reactor Owners Group (PWROG) Project Authorization (Reference 3). Responses to the NRC requests for additional information were transmitted in Reference 4.

Following receipt of our responses, the NRC issued a second set of RAIs dated March 23, 2007 (Reference 5). Attachment 1 provides the responses to this new set of RAI's. Enclosures 1-4 supply supporting information to respond to RAI #2 within this new set of RAI's.

If you have any questions concerning this matter, please feel free to call Reginald Dulaney at 412-374-6549.

Sincerely yours,

Electronically Approved
R. R. Dulaney approving for T. Schiffley

Frederick P. "Ted" Schiffley, II, Chairman
Pressurized Water Reactor Owners Group

FPS:RRD:mjl

Attachment: 1. Responses to 8 additional questions from previous RAI responses

Enclosures: 1. Data Sheets from test laboratories documenting leachable chlorides from epoxy coatings; 21 pages,
2. Letter from PPG/Keeler and Long to John Gisclon date July 16, 2004 documenting exchange with NRC on testing for leachable chlorides,
3. Letter from Analytical Consulting Technology Inc dated July 12, 2004 identifying the interpretation of the leaching test data used in response to RAI #2 is correct.
4. F. Dacquait et.al. "Corrosion Product Transfer in French PWRs During Shutdown," SFEN-Chimie 2002 Conference on Water Chemistry in Nuclear Reactor Systems, Avignon, France (2002).

cc: Systems & Equipment Engineering Subcommittee
Steering Committee
S. Peters - NRC
W. Rinkacs - Westinghouse
A. Lane - Westinghouse

Attachment 1

RAI #1

Your response to RAI #10 appeared to address the multi-part question except for the last part. Please respond to the following questions. Is it plausible for a containment pool at higher pH (e.g., 9 pH) to move a pH unit or more lower due to formation of nitric or hydrochloric acid after an accident? If so, why was no testing performed by adjusting pH from a higher value to a lower value?

RAI #1 Response

It is possible for minor perturbations to occur in the containment pool pH due to acid generation; however, utilities maintain a sufficient quantity of buffer in order to minimize this effect. The intention of the buffer is to maintain the pH of the sump solution. Once the pH of the sump solution has reached 9.0, the solution would be adequately buffered, i.e., sufficient buffer would be present, to account for any acid generation effects on the ultimate pH.

Testing a decrease in the pH would only provide information regarding the solubility of the precipitate. The model conservatively assumes 100% precipitation of the dissolved aluminum. Precipitation of aluminum due to downward shifts in the pH is fully included in the 100% precipitation assumption, so no testing of a downward adjustment in pH is necessary.

RAI #2

The response to RAI#13 indicated that data supporting a conclusion that insignificant chloride leaches from coatings was previously provided to the NRC and a reference was provided to a facsimile transmitted from the NRC staff to a coatings industry representative. The referenced data sheets from Keeler and Long/PPG Industries and Carboline Company, however, do not provide sufficient detail to fully respond to RAI#13. For instance, RAI#13 requested an estimate of chloride in the post-LOCA containment pool from leaching of containment materials (e.g., coatings).

Note: this topic was discussed during the February 8, 2007 public meeting on GSI-191. The PWR Owners Group indicated that they would respond to staff questions about potential interactions between coatings and chemical effects. If a separate response is provided to the NRC that addresses the question above, it will be sufficient to provide a reference to that response instead of repeating the information in the RAI response.

RAI #2 Response

The response to RAI#13 indicated that data supporting a conclusion that insignificant chloride leaches from coatings was previously provided to the NRC and a reference was provided to a facsimile transmitted from the NRC staff to a coatings industry representative. The referenced data sheets from Keeler and Long/PPG Industries and Carboline Company, however, do not provide sufficient detail to fully respond to RAI#13. For instance, RAI#13 requested an estimate of chloride in the post-LOCA containment pool from leaching of containment materials (e.g., coatings).

RESPONSE:

The following items are submitted in response to this RAI related to leachable chlorides in Epoxy coatings:

A summary of the translation of the quantity of leachable chlorides to a concentration in a typical sump volume, and,

- Enclosure 1. Data Sheets from test laboratories documenting leachable chlorides from epoxy coatings; 21 pages,
- Enclosure 2. Letter from PPG/Keeler and Long to John Gisclon date July 16, 2004 documenting exchange with NRC on testing for leachable chlorides,
- Enclosure 3. Letter from Analytical Consulting Technology Inc dated July 12, 2004 identifying the interpretation of the leaching test data used in the response presented below is correct.
- Enclosure 4. F. Dacquait et.al. "Corrosion Product Transfer in French PWRs During Shutdown," SFEN-Chimie 2002 Conference on Water Chemistry in Nuclear Reactor Systems, Avignon, France (2002).

The information in this response and the three enclosures to this letter provide leachable information for epoxy coatings from test data, a calculation of the result of leaching of chlorides from epoxy on resulting chloride concentration in the recirculation sump fluid, and supporting information from both a coatings vendor and a test lab.

Presented below is a summary of the translation of the quantity of leachable chlorides to a concentration in a typical sump volume.

ASSUMPTIONS:

1. 1250 cubic feet of coating inside a large dry containment; typical for a 4-loop PWR (10 mils thickness ~ 1,500,000 sq ft surface area)
2. 1% of all coating inside containment is submerged and subject to leaching (12.5 cubic feet – coatings on containment floor and coatings debris)
3. 80,000 cubic feet of coolant in sump (typical for 3-loop PWR – from the ICET test plan)
4. All leachable material from the submerged coatings is deposited in containment sump inventory.
5. 100 ppm leachable material – from letter from letter from Analytical Consulting Technology Inc dated July 12, 2004

CALCULATING THE VOLUMETRIC CONCENTRATION of LEACHABLE CHLORINE:

Equation used:

$$\text{Volumetric Concentration}_{\text{Leachable Chlorides, Coatings}} = \frac{\text{Coatings Volume} \times \text{Leachable Fraction}}{\text{Volume of Recirculation Fluid Inventory in Sump}}$$

$$\text{Volumetric Concentration}_{\text{Leachable Chlorides, Coatings}} = \frac{12.5 \text{ ft}^3 \times (100 / 1,000,000)}{80,000 \text{ ft}^3}$$

$$\text{Volumetric Concentration}_{\text{Leachable Chlorides, Coatings}} = 15.6 / 1,000,000,000 = 15.6 \text{ ppb}$$

The volumetric concentration value calculated above, 15.6 ppb (parts per billion) is conservative as it maximizes the coating volume (large dry 4-loop PWR) and minimizes the water volume (3-loop PWR).

Even if one assumes all the epoxy coating in the calculation is subject to leaching, and all of the leachable material in the epoxy coatings was deposited in the containment sump inventory, the resulting concentration is only 1.56 ppm (parts per million). This value is very small and is considered insignificant as a chemical reactant.

RAI #3

The reference provided in response to RAI #14, "The Chemistry of Fuel Crud Deposits and Its Effect on AOA (Axial Offset Anomaly) in PWR Plants," provides the basis for the response that 12 to 25 kilograms of crud material represents the upper bound of what could be released during a large-break LOCA. Table 3 in the above reference, under the Polley/Pick Plant Analysis column, indicates a total oxide on stainless steel in the range of 2 to 11 kilograms. Should this value be added to the 12 to 25 kilograms oxide on Inconel to estimate the total amount of corrosion product that could be released from the internal surfaces of the reactor coolant system during a LOCA? Discuss how these oxides may affect the sump strainer. The previous response to RAI #15 indicated that this particulate will be dense and tend to settle. Estimate the percentage of these oxides that may be transported to the strainer and the possible impact on head loss.

RAI #3 Response

It would be reasonable to add the 11 kg of stainless steel oxide to the 25 kg of Inconel oxide mentioned in the reference to produce a bounding oxide mass of 36 kg in the Reactor Coolant System (RCS). This does not alter our conclusion that RCS corrosion product release will have no effect on sump screen performance.

Another reference¹ has been provided, to shed light on the fraction of the oxide that might be released and transported. Over 80 shutdowns were examined, and the amount of material removed from piping surfaces during a shutdown never exceeded 20% of the total. A 20% release was the minimum detection limit for the measurement. Approximately 75 percent of the particles had a particle size greater than 10 microns. Thus, at most $36 \times 0.2 = 7.2$ kg would be expected to be released. The particle size would be quite large, so much less than this quantity would be transported to the strainers. Based on a density of 3.8 to 6.4 g/cm³, this equates to a maximum 0.07 ft³ of oxide, which is only 0.84 ppm for an assumed sump volume of 80,000 ft³. Due to the small quantity of material which makes it to the strainers, the head loss impact due to oxides would be negligible.

Reference to RAI #3 response:

1. F. Dacquait et.al. "Corrosion Product Transfer in French PWRs During Shutdown," SFEN-Chimie 2002 Conference on Water Chemistry in Nuclear Reactor Systems, Avignon, France (2002).

RAI #4

RAI#15 addressed potential effects from the release of radioactive species during the LOCA and their subsequent affect on the containment pool chemistry. Discuss the possible effects from radiolysis of water within the containment pool and reactor vessel that could modify the reduction potential (i.e., redox potential) of the water depending on the relative amounts of H₂, O₂ and H₂O₂ produced. This could potentially alter corrosion rates, chemical speciation and the solubility of compounds. Discuss the basis for not needing to account for radiological effects in the chemical model.

RAI #4 Response

Per the reference provided below, the concentration of H₂O₂ present in the reactor coolant during shutdown achieves a maximum concentration of 1 to 12 ppm about 24 to 48 hours after establishing acid-oxidizing conditions, and is on the order of 2 ppm for the balance of shutdown. This represents a good high estimate for the H₂O₂ concentration under post-LOCA conditions. Consideration of the dilution resulting from flood up to the sump volume from the reactor coolant system volume results in a maximum level of less than 1 ppm.

Hydrogen (H₂) has a similar radiolytic yield to H₂O₂ and thus similar concentrations would be expected. The quantity of hydrogen produced from radiolysis would be negligible when compared to hydrogen production from corrosion of aluminum.

As discussed above, the quantities of hydrogen (H₂) and hydrogen peroxide (H₂O₂) produced from radiolysis of water are low and would not be present in sufficient concentration to measurably influence material release rates. Likewise, the quantity of O₂ produced from breakdown of radiolytically-produced H₂O₂ is low and is negligible when compared to atmospheric oxygen.

Reference to RAI #4 response:

1. EPRI Report 11002884, Rev. 6, *Pressurized Water Reactor Primary Water Chemistry Guidelines, Volume 1, Appendix E*, EPRI, Palo Alto, CA, 2006.

RAI #5

The response to RAI #16 indicated that the dissolution behavior of concrete is expected to be consistent between U.S. PWR sites. The response appeared to address the question except for the following. Please provide the composition and applicable specifications for the concrete tested. Was the concrete tested representative of concrete in the U.S. PWR plants?

RAI #5 Response

The chemical constituents of the sample were determined by SEM-EDS and are available in the WCAP. The base chemical constituents available for dissolution are not significantly affected by different preparations of concrete. The model is concerned with the dissolution of the chemical constituents. In this respect, the dissolution behavior of the concrete sample tested would be representative of concrete in US PWR plants.

From discussions with a representative of the Portland Cement Association, the significant differences in terms of chemical makeup between any concrete mixes rated at differing compressive strengths are (1) the type of Portland cement used, (2) the nature of the coarse aggregate, and (3) the cement-to-water ratio.

It is known that the sample analyzed was 4000-psi concrete that incorporated ASTM C-150 Type II Portland cement and coarse aggregate in compliance to ASTM C-33, and was cured in excess of 28 days. These specifications also apply to typical 6000-psi concrete used in containment. Thus, the sample is representative of concrete used in containment.

The sample itself was prepared such that the coarse aggregate was not pulverized with the remainder of the sample, and only the crushed "matrix" material was used in the dissolution testing. Per the Portland Cement Association, the overwhelming difference in the pulverized matrix material between 4000-psi and 6000-psi concrete mixes is the cement-to-water ratio employed in the original mixture and hence, once cured, pulverized matrix samples from 4000-psi and 6000-psi concrete would be very similar with respect to their chemical makeup. Thus, the sample is representative of concrete used in containment.

Moreover, a comparison of detailed concrete specifications is deemed unnecessary with respect to dissolution testing because testing of the chemical constituents of concrete – with respect to dissolution in the sump fluid - is dependent on the exposed surface area. Applicable specifications dealing with structural characteristics are intended to prevent concrete corrosion by precluding increased surface area (via cracks) for the sump solution to attack the concrete medium. As mentioned in WCAP-15630-NP, the concrete dissolution rate is determined by the exposed surface area of the concrete. By grinding up the concrete sample, high surface areas of the chemical constituents are in contact with the sump solution, accelerating the dissolution rate

relative to in-situ concrete in containment, and the model does not scale the rate of dissolution to the account for the lower surface area actually present in containment.

RAI #6

In the October 4th NRC letter, RAI #23 and RAI #25 were related to WCAP-16530-NP Equation 6-1 and Equation 6-2 aluminum release rates, respectively. In particular, the staff questioned whether there might be a better fit to the aluminum corrosion rate data. In response to RAI #24, a corrected value was provided for the “B” coefficient in Equation 6-1 and it was stated that Equation 6-1 was not used in the chemical model. RAI #24 discussed the corrosion of aluminum during the Integrated Chemical Effect Test 1 (ICET 1), that appeared to occur in stages. The initial ICET 1 corrosion rate (i.e., during the initial 10 days of testing) appears to be approximately 30 mg/m²-min. Following an initial linear rate of aluminum dissolution, the corrosion rate appears to decrease and eventually the dissolved aluminum measurements seem to indicate some type of aluminum coupon passivation. Please provide a table that evaluates the following coefficients (relative to Equation 6-2) for fit to the WCAP data and for the initial 15 days of ICET 1. Discuss whether the coefficients in Equation 6-2 or the coefficients below would be more appropriate for the aluminum release rate in the chemical model.

a = 12.950
b = 0.540
c = -4.467
d = 0.014
e = -1.413

RAI #6 Response

The coefficients as provided by the NRC in RAI #6 for modeling the aluminum corrosion do provide a reasonable fit to the “bench top” data. The table below shows the comparison for the WCAP bench top data. However, the coefficients used in the WCAP were introduced to improve the prediction for a data set that included aluminum release rate measurements from ICET #1 as well as measurements from Oak Ridge (CR-6873) and previous Westinghouse work (WCAP-7153A). The fit to the expanded data set was shown in WCAP-16530-NP.

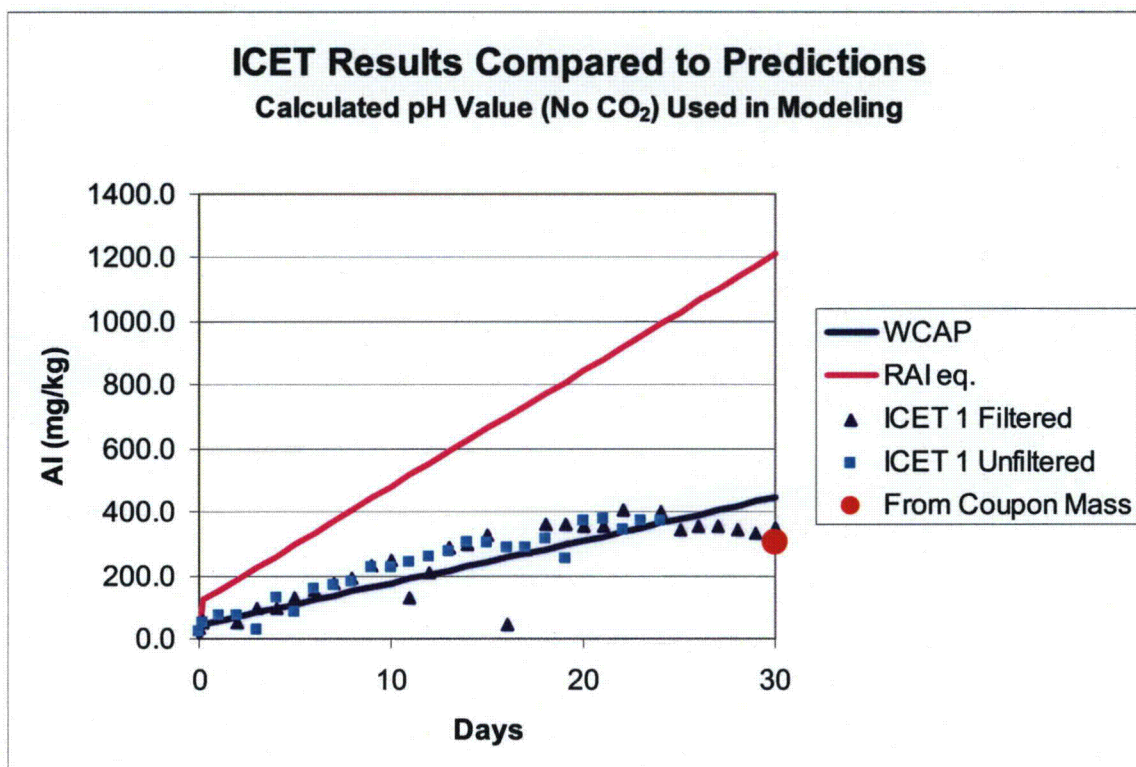
Temp	pHa	Meas. log RR	WCAP Predicted log RR	RAI Predicted log RR
190	4.1	0.968	0.79	0.93
190	8	1.650	1.20	1.71
190	12	3.001	3.03	2.95
265	4.1	1.952	1.92	1.97
265	8	2.597	2.13	2.52
265	12	3.524	3.76	3.52

RR = release rate in mg/m²-min

A more detailed look at the ICET 1 results and the prediction from each model is shown below. A pH of 10 was used for ICET 1 pH. This was the pH of the solution predicted for no CO₂

adsorption from the atmosphere. This pH was used rather than the measured pH values, just the same as for the WCAP-16530-NP bench top testing. This was done to be consistent with post LOCA pH predictions used in the industry, which also do not include predictions from CO₂ adsorption from the containment atmosphere. The predictions in the figure also included the corrosion from the initial spray phase, where the pH of the spray solution was assumed to be 10.

The WCAP-16530-NP prediction is more representative than that made with the coefficients suggested in this RAI.



RAI #7

The response to RAI #47 talks about the one hour settling volume of surrogate precipitates. Please address the final part of RAI #47, i.e., discuss how consistency in surrogate settling data interpretation and settling test technique are maintained between these tests and those that may be performed by strainer vendors. In addition, discuss whether any changes have been made or are planning to be made to the surrogate settlement acceptance criteria considering the recent observations made at a vendor facility that showed aged surrogate met the settlement criteria but apparently underwent physical changes that affected head loss.

RAI #7 Response

The settling rate criteria for the aluminum precipitates provided in the WCAP will be revised to require higher settled volumes during the one hour test to provide added assurance that the surrogates behave in a prototypical manner. Narrowing the band of the settling rate criteria will

eliminate the need for the shelf life criteria and address any concerns regarding appropriate use of the surrogates. The settling rate test guidance in the WCAP is intended to provide consistency between strainer vendors.

RAI #8

The response to several RAI's (e.g., RAI #29, RAI #43) indicate that the surrogate materials were chosen to be representative of the settling and filtration characteristics of precipitates that may form in prototypical plant conditions. Therefore, exact chemical identification of the precipitates that formed during the WCAP-16530-NP testing was not necessary. In the event that future tests are performed to support removing some of the model's conservative assumptions, for example that all dissolved material precipitates, it is important to understand the nature of the precipitate (e.g., boron adsorption affects the structure of amorphous aluminum hydroxide which affects solubility). Therefore, discuss if you have plans to more fully characterize precipitate chemistry to support future model refinements.

RAI #8 Response

There are currently no plans to further characterize surrogate materials as part of the effort presented in WCAP-16530-NP. Evaluation of the need for additional characterization of the surrogates to support other work will be performed as part those efforts. For example, additional characterization of the surrogates may be required to support the determination of solubility limits as part of the plant-specific inputs effort under the PWROG program, PA-SEE-0354.

SECTION E



Program Management Office
4350 Northern Pike
Monroeville, Pennsylvania 15146

WCAP-16530-NP, Rev. 0 (Non-Proprietary)
Project No. 694

September 12, 2007

OG-07-408

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Subject: Pressurized Water Reactor Owners Group
Responses to NRC Requests for Clarification Regarding WCAP-16530,
"Evaluation of Chemical Effects in Containment Sump Fluids to Support GSI-
191" (PA-SEE-0275)

References:

1. PWR Owners Group letter, OG-07-129, "Pressurized Water Reactor Owners Group Responses to the NRC Second Set of Requests for Additional Information (RAI's) on WCAP-16530, 'Evaluation of Chemical Effects in Containment Sump Fluids to Support GSI-191'," April 3, 2007.
2. NRC letter from Sean E. Peters of NRR to Gordon Bischoff of PWROG dated March 23, 2007, "REQUEST FOR ADDITIONAL INFORMATION RE: PRESSURIZED WATER REACTOR OWNERS GROUP TOPICAL REPORT (TR) WCAP-16530-NP, 'EVALUATION OF POST-ACCIDENT CHEMICAL EFFECTS IN CONTAINMENT SUMP FLUIDS TO SUPPORT GSI-191' (TAC NO. MD1119)."
3. WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February 2006.

Subsequent to the Pressurized Water Reactor Owners' Group (PWROG) submittal of responses (Ref. 1) to Nuclear Regulatory Commission (NRC) Request for Additional Information (Ref. 2), NRC in several instances requested additional clarifications via informal correspondence regarding WCAP-16530-NP (Ref. 3).

The attachment to this letter summarizes PWROG responses to these requests and represents final resolution of open items on the Ref. 3 topical report.

Enclosures 1 through 6 represent information referred to in Attachment 1 but which has not been previously transmitted formally to NRC.

If you have any questions regarding the attached or the contents of this letter, please contact John Maruschak (412-374-3512) or any of the undersigned.

Regards,

Reginald Dulaney Approving for T. Schiffley

Frederick P. "Ted" Schiffley, II, Chairman
Pressurized Water Reactor Owners Group

FPS:RRD:mjl

Attachment: PWROG Responses to requests for clarification and supplemental information regarding WCAP-16530-NP

- Enclosure 1 Ken Johnson, Kenny Epperson, "Recent Shutdown Releases at McGuire," PWR Primary Shutdown Workshop, EPRI Offices, Charlotte, June 9-10, 2004.
- Enclosure 2 Excel spreadsheet entitled "ICET1 Al pred NRC vs WCAP Calculated pH no CO2.xls"
- Enclosure 3 Reid, R.E., "Evaluation of the Filterability of WCAP-16530-NP Aluminum Oxyhydroxide Precipitate Surrogate," Westinghouse Letter LTR-CDME-07-115, May 22, 2007.
- Enclosure 4 Westinghouse Document "Flow Rate and Differential Pressure Curves for the Constant Flow Rate Filtrations_Final-06192007.doc"
- Enclosure 5 Westinghouse Document "Autoclave Filterability Tests Draft 2.pdf"
- Enclosure 6 Westinghouse Document "Short summary – Results of filterability testing 207 – 2007-08-13.doc"

cc: Systems & Equipment Engineering Subcommittee
Sean Peters, USNRC
Paul Klein, USNRC
John Lehning, USNRC
Alan Hiser, USNRC
Stacey Rosenberg, USNRC
Tanya Mensah, USNRC
John Maruschak, Westinghouse
William Rinkacs, Westinghouse
Art Byers, Westinghouse
Rick Reid, Westinghouse
Tim Andreychek, Westinghouse
PMO

PWROG Responses to Requests for Clarification and Supplemental Information Regarding WCAP-16530-NP

The following items, numbered 1 through 8, refer to NRC requests for clarification on the same-numbered responses submitted via Ref. A.

1. **NRC COMMENT:**

No further information requested.

2. **NRC COMMENT:**

The purpose of the response is to demonstrate a very low number for leachable chlorides in terms of the post-LOCA containment pool volume using conservative assumptions (e.g., 4 loop coating volume, 3 loop water volume). Two questions:

(1) given the conservative nature of other assumptions, and leachable chloride data sheet values from a few ppm to over 600 ppm, why is 100 ppm selected for the calculation?

(2) the data sheets provide leachable chloride as a mass concentration but the calculation appears to use the data as a volumetric concentration. Should these numbers be adjusted with consideration of the coating's specific gravity?

RESOLUTION:

The 100 ppm figure used was intended for use in an illustrative calculation. In retrospect, use of a higher value to bound the sump chloride concentration would have been a better approach.

Regarding the concept of mass versus volume concentration, it is recognized that various coatings manufacturers, as well as various formulations for coatings from the same manufacturer, have differing solids contents and consequently differing specific gravities. The volume concentration expression, however, is independent of solids content.

As the objective of the ICET test was to be inclusive of all plants, the volume concentration approach was chosen for the ICET test because it is independent of solids content, or specific gravity, of the coatings. Data reflecting the solids content of the coatings for which leaching data sheets were obtained was not available at the time the evaluation was being made to not test epoxy coatings for the ICET test.

Given the volume concentration, the mass concentration can be determined by multiplying the volume concentration by the specific gravity of the specific coating. An expected range of specific gravities for DBA-qualified epoxy extends from approximately 1.05 to 1.35

This being said, and for completeness, the following calculation – based on mass concentration - is offered as a bounding analysis to address the subject of chloride concentration:

Minimum reported sump volume at any plant: $20,400 \text{ ft}^3 = 577,320 \text{ L}$

Total submerged coating area: $150,748 \text{ ft}^2$

Conservative paint thickness: $10 \text{ mils} = 8.33\text{E-}04 \text{ ft}$

Conservative density of cured paint: $2 \text{ g/cm}^3 = 56,634 \text{ g/ft}^3$

Conservative leachable chloride content: 700 ppm (mg/kg)

PWROG Responses to Requests for Clarification and Supplemental Information Regarding WCAP-16530-NP

Resulting sump concentration (ppm by weight; i.e., mg/kg):

ppm Cl⁻ in Sump = mg Cl⁻ / Kg sump mass

mg Cl⁻ = (150,748 ft²) * (8.33E-04 ft) * (56,634 g/ft³) * (1Kg/1000g) * (700mg Cl/Kg Paint) = 4,978,194 mg Cl⁻

Sump Mass = 577,320 L * 1kg/L = 577,320 Kg

Sump Concentration: (4,978,194 mg Cl⁻) / (577,320 Kg sump mass) = 8.6mg Cl⁻/Kg sump solution = 8.6ppm.

To summarize, using an **extremely conservative** situation where the **conservatism**s are **compounded**, the upper-bound chloride concentration in the sump is calculated to be 8.6 ppm, which is negligible in light of the fact that this value is a **factor of eleven** smaller than the 100 ppm Cl added in ICET 1-4 and a **factor of five** lower than the 43 ppm added in ICET 5. Fluctuations in sump fluid density due to temperature are not significant enough to overcome a factor of 5 or 11.

3. NRC COMMENT:

Based on the French data, the RAI response assumes 20% of the oxide would be released and transport to the pool. Would the percentage of RCS oxide released during and subsequent to a LOCA be substantially higher than the value obtained from the study of 80 shutdowns? In addition, the RAI response indicates about 75% of the particles had sizes greater than 10um. Should the particle size distribution for a LOCA be similar to the data shown for 3 days prior to shutdown, i.e., about 75% in the 5 um to 10um range?

RESOLUTION:

The corrosion products released from the RCS in a PWR LOCA would be small. The theory and data supporting this conclusion are given as follows.

The two primary means for corrosion product release during an outage are chemical dissolution and physical shocks (Ref. B). The chemical dissolution is the result decreasing temperature, decreasing pH due to increased boron and decreasing temperature, and a change in the electrochemical potential of the system. The electrochemical potential will change from low values during operation to high values due to exposure to containment oxygen. The physical shocks will be generated by high fluid flows, and vibrations, and thermal expansion and contraction.

The LOCA release of corrosion products by chemical dissolution is expected to be similar to that experienced during a normal shutdown because the chemistry changes in the coolant during a LOCA will be similar to those experienced during a normal shutdown. The decrease in pH to approximately pH 5 (increased acidity) due to cooling and the addition of boric acid to 2500 ppm during a normal outage parallels the initial pH decrease during a LOCA. During a LOCA, the pH will return to higher values, typically between pH 7 and pH 8 due to the addition of buffer agents such as sodium hydroxide. This is similar to the return to pH 7 to 7.4 that PWR experiences during a normal start-up. During a normal shutdown extreme changes in electrochemical potential are induced to remove corrosion products. This is done by adding hydrogen peroxide to the RCS. During a LOCA, the chemical shock would be primarily caused by the admission of oxygen, a less potent oxidizing agent, from containment. Thus, normal shutdown releases by chemical dissolution can be used to bound LOCA releases.

Westinghouse knowledge of shutdown releases during normal refueling outages was reviewed to obtain a high estimate for a LOCA release due to chemical factors. Based on an informal compilation by Westinghouse of shutdown releases from 113 outages, the peak nickel concentration at a PWR due to peroxide addition at a normal shutdown was 13.93 ppm, which was associated with a rapid release of 5.4 kg of nickel. The total average nickel release for the industry is 2.9 kg per outage, and the maximum Ni release to date is 8.1 kg for an entire outage. With iron concentrations during outages typically below 1 ppm (and thus certainly less than

PWROG Responses to Requests for Clarification and Supplemental Information Regarding WCAP-16530-NP

1 kg total, even for the largest PWR RCS volumes), it is reasonable to use an estimated high value of 10 kg release due to chemistry changes during a LOCA.*

PWR corrosion product releases due to physical shocks are minimal. For instance, at the plant from this data compilation with the record shutdown nickel coolant concentration, shortly before the large chemically-induced release, one reactor coolant pump was turned off while another was started. There was no increase in coolant corrosion product concentrations. At another plant where coolant iron and nickel concentrations were recorded at record high levels during the cycle, the nickel concentration upon restart of the RCPs for the subsequent cycle increased by less than 1 ppm. Although flow changes due to a LOCA break may be greater than that at RCP start/stop, it has been shown that even for extreme agitation such as during fuel ultrasonic cleaning, there is not much material released beyond the initial chemically induced crud release. For instance, a study of ultrasonic cleaning of highly crudded fuel showed a release of 2.3 grams of corrosion product per assembly. This corresponds to bounding physical agitation release of 0.45 kg for the entire core. Typically, the crud released from the core is 37.4 percent of the total release during a normal end of cycle shutdown (Ref. C). Thus, a high estimate of 1.2 kg release from a PWR due to physical shocks is reasonable.

Thus, a bounding number for total release of RCS corrosion products during a LOCA is estimated to be 11.2 kg. Of this total, a maximum of 10 kg will be released as a result of chemical reactions and a maximum of 1.2 kg will be released from physical shocks.

RCS corrosion products released during a LOCA will be similar to those released during a normal outage, and as a result, will not present any unexpected problems. These corrosion products will be either dissolved, as in the case of nickel, or will be particulates that are relatively large compared to solid matter formed from chemical reactions in the sump. PWRs often measure the particulate fraction during a shutdown, and the particulate release always represents a small fraction of the total release. A study of corrosion product release at four different PWRs (Ref. 4) reveals that this dissolved fraction averaged 90% over 16 different outages. Applying a conservative ratio of 50% (which bounds the range of all 16 of these data points) to the bounding corrosion product release calculated herein results in a remainder of 5.6 kg in particulate form.

Finally, particle size analysis has shown that 75% of the particles are larger than 10 microns in diameter. (Ref. D). Applying this ratio results in 4.2 kg in particulates 10 microns or greater in diameter and the remaining 1.4 kg in particulate form less than 10 microns or less in diameter.

** Specific activity of 1.575 Curies per gram nickel assumed in calculations involving specific activity.*

4. **NRC COMMENT:**

No further information requested.

5. **NRC COMMENT:**

No further information requested.

6. **NRC COMMENT:**

Staff would like to get a copy of the calculations used to develop the figure.

PWROG Responses to Requests for Clarification and Supplemental Information Regarding WCAP-16530-NP

RESPONSE:

The spreadsheet (Ref. E) was transmitted to NRC staff via e-mail on May 16, 2007

7. **NRC COMMENT:**

What is the revised settling rate acceptance criteria?

RESOLUTION:

WCAP-16530-NP will be annotated (specifically, Figure 7.8-1 and the text in Sections 7.3.2, and 7.6) to make reference to the following statements:

- For future head loss tests in which the objective is to keep chemical precipitates suspended (e.g., via tank agitation):
 - For sodium aluminum silicate and aluminum oxyhydroxide, the settling rate should be measured within 24 hours of the time the surrogate will be used and the 1 hour settled volume shall be 6.0 ml or greater and within 1.5 ml of the freshly prepared material.
 - For calcium phosphate, settling rate should be measured within 24 hours of the time the surrogate will be used and the 1 hour settled volume shall be 5.0 ml or greater and within 1.5 ml of the freshly prepared material.
 - Testing should be conducted such that surrogate material is introduced in a way to ensure transportation of all material to the screen.
- For future head loss tests in which the objective is to settle chemical precipitates and other debris, surrogates that settle equal to or less than the 2.2 g/L concentration line shown in Figure 7.6-1 of WCAP-16530-NP (i.e., 1 or 2 hour settlement data on or above the line) are acceptable. Settling rate should be measured within 24 hours of the time the surrogate will be used.
- For those utilities that have performed testing using existing settling rate criteria, the following observations should be noted:
 - Testing performed by Pacific Gas and Electric Company (PG&E) showed that the settling rate and filtration properties of the sodium aluminum silicate surrogate were essentially constant over time.
 - The PG&E testing also showed that, although the settled volume of the aluminum oxyhydroxide surrogate slowly decreased over time, the head loss caused by the surrogate material increased over time, and thus head loss testing performed using the surrogate material was conservative.
- On the basis of these observations, previous testing performed using surrogate material evaluated under existing settling rate criteria are considered valid for head loss tests in which the objective was to keep chemical precipitates suspended and for which this objective was met.

8. **NRC COMMENT:**

No further information requested.

Attachment to Letter OG-07-408

PWROG Responses to Requests for Clarification and Supplemental Information Regarding WCAP-16530-NP

Items designated “+1” and “+2” below refer to additional NRC requests for clarification subsequent to submittal of Ref. A.

“+1” **NRC COMMENT:**

Is there data that compares the filterability of sodium aluminum silicate to aluminum oxyhydroxide?

RESOLUTION:

Referring to Attachment 2 to Ref. F, the following information is available:

Precipitate Filter Coefficients

PPT Run	Precipitation Formation Method	Individual Filter Cake Coefficients (K_{fx})	PPT Type
2	PPT on cooling, Al pH 8	0.0033	AlOOH
24a	PPT on cooling, FibreFrax, pH 12	0.0066	NaAlSi ₃ O ₈
24b	PPT on cooling, FibreFrax, pH 12	0.0043	NaAlSi ₃ O ₈
24c	PPT on cooling, FibreFrax, pH 12	0.0027	NaAlSi ₃ O ₈
24d	PPT on cooling, FibreFrax, pH 12	0.0039	NaAlSi ₃ O ₈

Comparing the K_{fx} values above, there is not a significant difference between the precipitate forms in terms of filterability.

Furthermore, data collected from additional Westinghouse filtration tests (Ref. G) provide further evidence that there is no statistical difference between the sodium aluminum silicate and aluminum oxyhydroxide.

“+2” **NRC COMMENT:**

Does Westinghouse have any insights as to why the K_{fx} for aluminum oxyhydroxide in 4400 ppm boron is at least an order of magnitude lower than the value in tap water [see Ref. F, response to RAI #44]

RESOLUTION:

In addition to Westinghouse review of the original WCAP-16530-NP technical basis, further Westinghouse testing confirms the validity of the test methodology and supports the conclusion that the use of surrogate materials results in conservative pressure drops in screen testing, irrespective of whether the surrogates are prepared in tap water or boric acid solution. (Refs. G, H, J, K)

PWROG Responses to Requests for Clarification and Supplemental Information Regarding WCAP-16530-NP

In addition to the follow-on requests for clarification in regard to responses transmitted in Ref. A, following are supplemental clarification requests and resolutions since the Ref. A submittal:

NRC COMMENT:

Aluminum Release Rates

Prediction of aluminum release is very important since it accounted for approximately 3/4 of the total mass released during the WCAP testing. The RAI response and ICET data fit compares the results with the average Al corrosion rate over 30 days, even though the Al passivated around day 15 or so. The existing release rate equation underpredicts the dissolution in the early part of ICET and the staff questions using a 30 day average rate, for example, to compute dissolution during the spray phase. The rate should be computed during the active corrosion phase and then an argument made whether passivation should or should not occur at some point. Staff also questions whether the use of a target pH 10 to fit the ICET-1 data is appropriate for model fit. The best estimates of the pH in the test should be used. In ICET-1 we have measurements through the test.

RESPONSE:

In the WCAP-16530-NP text, after equation 6-2, the following statement will be referenced in annotation:

“At intermediate times (i.e., less than 30 days), Equation 6.2 will underpredict the release rate. Hence, the cumulative 30-day integrated aluminum corrosion product release value predicted by the WCAP-16530-NP model should be used for screen testing, even if an intermediate time period is being simulated. If a cumulative value at an intermediate time is desired, individual plants must justify the derivation of that value.”

NRC QUESTION:

What are the references for the theoretical filtration model?

RESOLUTION:

The model is a generalization of the model presented in Equation 28-13 on page 888 of Unit Operations of Chemical Engineering by McCabe and Smith (1967 edition). The terms of the model that involved individual particle parameters were lumped into the K value in the original equation since they would be largely indefinable with the type of gelatinous solids that would be formed in the current testing. The effect of multiple layers (including the filter itself) on the analysis of the data using this model is derived from Equation 28-21 on page 892 of the same reference. Again, the particle descriptive terms were lumped into the K value due to the indefinable nature of the solids in this type of testing. This multiple layered approach is the same as is used in the analysis of heat transfer through multiple layers of insulation, vessel walls and boundary layers.

NRC QUESTION:

For what types of filtering media (e.g., fiber, fiber/particulate, amorphous product) and filtrate conditions (e.g., flow, dP, debris bed loading) has the model been shown to be valid?

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RESOLUTION:

The model above is totally general and would apply to all of our conditions. The only possible exceptions would be if the solids and debris beds would be highly compressible or if the flow of liquid through the bed of particles or debris would be high enough to be in the turbulent region. For either case, the particulate bed would have the majority of the pressure drop. Because of the small size of the particles (~1 micron), the flow through the bed would be laminar. Also, because of the very thin (~1 mm thick) cakes that were formed which resulted in pressure drops of several psi, the bed would not be compressible. Since we used a filter that was not compressible, there is linear behavior in our lab tests. This is borne out by the fact that the flow rate as a function of pressure drop curves were indeed linear. As far as the plant scale tests go, we do not know what the debris bed is. Again, since the tests are carried out under conditions of relatively low delta P (you indicated ~5 to 7 psi), I would doubt that there would be any significant effect of the debris bed on pressure drop even if it were somewhat compressible.

NRC QUESTION:

How does the WCAP test data (and subsequent data) compare with the model predictions?

RESOLUTION:

The model was used to generate the Kx values for various solids as a means to compare the different types of solids generated under different conditions on the same basis. Upon further clarification of the question as to the variability of the data, at the time, not enough testing was done to generate a good measure of test variability. The low variability of these tests has since been confirmed with additional test data.

NRC QUESTION:

Looking back at my notes, I also had one specific question on the text in the revised Section 5.4 in the WCAP RAI response. [Attachment 2 to Ref. F.] The model assumed (pg. 29 of 35) that the debris bed is relatively thin and incompressible based upon the applied pressure drops being very small (on the order of 1 to 6 psi). Yet isn't this model being used also for test data taken at higher pressure drops (e.g., in excess of 40 psi)?

RESOLUTION:

Even at the high pressure drops, the flow rate versus pressure drop curves were still reasonably linear. So again, because of the thin cake that was formed and the nature of the precipitate, the model assumption of an incompressible bed and therefore linearity still is valid.

NRC QUESTION:

Can the debris layer and amorphous layer truly be considered separate beds? Will the materials get into the filter media?

RESOLUTION:

In our filter tests, the pore size of the filter media was very small so that this effect is not likely to occur and the Kx of the filter and the solids would be separable. For actual debris beds, the effect of solids that are held up inside the bed is not modelable because of the variability of the beds and solids and the unknown interactions between the particles and debris bed materials. However, one could say that if the debris bed had

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very tight pores compared to the precipitates, it would act like the filter paper in the Westinghouse testing and the Westinghouse model would be directly applicable as far as the pressure drop that a given amount of like solids per area would cause. If the debris bed had pores that were significantly larger than the particles, then the Westinghouse model would significantly underestimate that amount of solids that could be put on the filter before the same pressure drop was obtained. However, the Westinghouse model could not calculate how much more solids could be added before the same pressure drop would be obtained.

NRC QUESTION:

Is anymore data available?

RESOLUTION:

Additional filterability data is available in References G, H, K, and L.

NRC EDITORIAL COMMENTS ON WESTINGHOUSE RAI RESPONSES PROVIDED IN REF. F

Possible typos in the head loss discussion in the WCAP RAI response include:

- last sentence on page 33 of 35, should the description of K_{fs} refer to the screen coefficient?

Response: Acknowledged. This is a typographical error and should read:

The K_{fs} (filter coefficient) was obtained from the slope (z) of the dP versus flow measurement for the filter (Figure C-1) using the equation:

- page 30 of 35, should the units for K_{fs} have cP to the first power, as opposed to the negative first power?

Response: Acknowledged. This is a typographical error. The line

$K_{fs} = \text{the screen coefficient (gpm ft}^{-2} \text{psi}^{-1} \text{cP}^{-1})$

Should read:

$K_{fs} = \text{the screen coefficient (gpm ft}^{-2} \text{psi}^{-1} \text{cP})$

- are the dimensions of K_{fs} in equation 5-7 the same as the dimensions of K_{fs} in equation 5-2?

Response: Acknowledged. This is a typographical error and should read:

$K_{fs} = n / A / z / [3785 \text{ ml/gal}]$

- similarly, are the dimension of K_f in equations 5-6 and 5-2 the same?

Response: Acknowledged. This is a typographical error and should read:

$K_f = n / A / z / [3785 \text{ ml/gal}]$

In addition to the above typographical errors identified by NRC, the following errors are noted:

- Page 29 of 35, the line:

$K_{fx} = \text{filter cake coefficient for a specific precipitate or solid x (gpm lb}_m \text{ cP ft}^{-4} \text{psi}^{-1})$

Should read:

$K_{fx} = \text{filter cake coefficient for a specific precipitate or solid (gpm lb}_m \text{ cP ft}^{-4} \text{psi}^{-1})$

- Page 29 of 35, the line:

$m_x = \text{specific dry (1 hour @ 110}^\circ\text{C) solids x loading (lb}_m \text{ ft}^{-2})$

Should read:

$m_x = \text{specific dry (1 hour @ 110}^\circ\text{C) solids loading (lb}_m \text{ ft}^{-2})$

- Page 29 of 35, the line:

4. The K_{fs} of the screen (gpm ft⁻² psi⁻¹ cP⁻¹) determined with the viscosity at the temperature of interest

Should read:

4. The K_{fs} of the screen (gpm ft⁻² psi⁻¹ cP) determined with the viscosity at the temperature of interest

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REFERENCES:

- A PWR Owners Group letter, OG-07-129, "Pressurized Water Reactor Owners Group Responses to the NRC Second Set of Requests for Additional Information (RAI's) on WCAP-16530, 'Evaluation of Chemical Effects in Containment Sump Fluids to Support GSI-191'," April 3, 2007.
- B PWR Primary Water Chemistry Guidelines: Volume 2, Revision 5, EPRI, Palo Alto, CA: 2003. TR-105714-V2R5, page 2-2.
- C F. Dacquait et.al. "Corrosion Product Transfer in French PWRs During Shutdown," SFEN-Chimie 2002 Conference on Water Chemistry in Nuclear Reactor Systems, Avignon, France (2002)
- D Ken Johnson, Kenny Epperson, "Recent Shutdown Releases at McGuire," PWR Primary Shutdown Workshop, EPRI Offices, Charlotte, June 9-10, 2004.
(See Enclosure 1.)
- E Excel spreadsheet entitled "ICET1 AI pred NRC vs WCAP Calculated pH no CO2.xls
(See Enclosure 2.)
- F PWR Owners Group letter, OG-06-387, "Pressurized Water Reactor Owners Group: Responses to the NRC Request for Additional Information (RAI) on WCAP-16530, 'Evaluation of Chemical Effects in Containment Sump Fluids to Support GSI-191'," November 21, 2006.
- G Reid, R.E., "Evaluation of the Filterability of WCAP-16530-NP Aluminum Oxyhydroxide Precipitate Surrogate," Westinghouse Letter LTR-CDME-07-115, May 22, 2007.
(See Enclosure 3.)
- H Westinghouse Document "Flow Rate and Differential Pressure Curves for the Constant Flow Rate Filtrations_Final-06192007.doc"
(See Enclosure 4.)
- K Westinghouse Document "Autoclave Filterability Tests Draft 2.pdf"
(See Enclosure 5.)
- L Westinghouse Document "Short summary – Results of filterability testing 207 – 2007-08-13.doc"
(See Enclosure 6.)